The global geoheritage significance of the Kimberley Coast, Western Australia

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Abstract

The Kimberley Coast in north-western Australia is of global geoheritage significance. It is a large-scale ria coast, with a well developed intricate indented rocky shoreline, with local nearshore islands (archipelago), and a distinct suite of coastal sediments. In addition to its intrinsic geoheritage values, its unique geological and geomorphological features are found in an unspoiled wilderness setting in which *the ensemble of natural processes are still operating*. The Kimberley Coast is cut into Precambrian rocks: the sandstones and basalts of the Kimberley Basin and, in the southern areas, into folded sedimentary rocks and metamorphic rocks of the King Leopold Orogen. The rocks of the region are well exposed along the shore to providing a global classroom by which to study the region's stratigraphy, structure, and lithology. The coastal forms in the Kimberley region have been determined by the structure and lithology of regional geology, interfaces between major geological units, by marine inundation of onshore landforms, and by the sizes, shapes and configuration of rivers, creeks, their tributaries, and other valley tracts in the region. The coast, however, is not just a continuous rocky shore composed of cliffs, and cliffs with benches, as it also has local sediment-filled gulfs and embayments, cliff shores fringed by mangroves, cliff shores with bouldery ribbons in the tidal zone, and stretches of beaches, and in the embayments, muddy tidal flats, spits, cheniers, tidal creeks cut into the tidal flats, and (embayment-head) alluvial fans. Locally, the coast is composed of algal reefs and coral reefs, beach rock, and various types of tempestites.

The Kimberley Coast presents several features of geoheritage significance: 1. with ~ 700 km of (simplified) coastal length, it presents the best and most extensive expression of ria morphology in Australia, and also one of the best developed globally; 2. the occurrence of the shore in a monsoonal subhumid/humid tropical macrotidal setting, with processes distinct to this setting; as a tropical-climate ria, in terms of size and morphology, it is globally unique; 3. the morphology of the shores, variable in form in response to the grain of the country (*viz.*, the Kimberley Basin *versus* the King Leopold Orogen) and lithology; 4. variation of rocky shores along its length in terms of mesoscale shore types; 5. the sedimentary packages that occur in the region; 6. mangrove-lined rocky shores and embayed shores, with the latter also related to freshwater seepage; and 7. biogenic and diagenetic coasts.

Keywords: Kimberley Coast, ria coast, tropical coast, macrotidal, Proterozoic rocks, geoheritage

Introduction

Globally, only a few coasts have been described and assessed as to their geoheritage significance and this paper provides an opportunity to describe the Kimberley Coast of Western Australia (Fig. 1) and address its geoheritage significance from an International and National perspective. While there have been studies and geoheritage assessments of some rocky coasts in Australia of National or of State-wide significance (*e.g.*, Hallett Cove in South Australia, The Twelve Apostles in Victoria, and Ulladulla cliffs and platform in New South Wales; Packham 1969; Parkin 1969; Dexel & Preiss 1995; White *et al.* 2003) and overseas (*e.g.*, Siccar Point in Scotland, The Seven Sisters of southern England, the Giant's Causeway in Ireland; Gallois 1965; Melville & Freshney 1982; Soper 1984; Bennett 1989; Sale *et al.* 1989; Jagla & Rojo 2002; Brocx & Semeniuk 2007), ironically, the Kimberley Coast, the largest rocky coastline in Australia and one of the most distinctive ria coasts globally, before now, has not been formally described and assessed for its geoheritage value.

Interestingly, because it is an extensive and essentially a single coastal unit, the Kimberley Coast challenges many concepts in natural science and classification in the coastal zone. For instance, the essence of what is a "ria coast" in plan form and relief is tested here, and the extremes of coastal types that constitute "ria shores" are present in this one region. For instance, geometrically, because of the regional geology, the ria coast of the Kimberley region grades from classic narrow ravines and inundated riverine valleys (traditionally, the most accepted notion of a ria) to broader embayments (indented coasts) to marine-inundated ridge-and-basin topography (also termed ridge-and-valley topography; Fairbridge 1968a). Apart from geomorphic

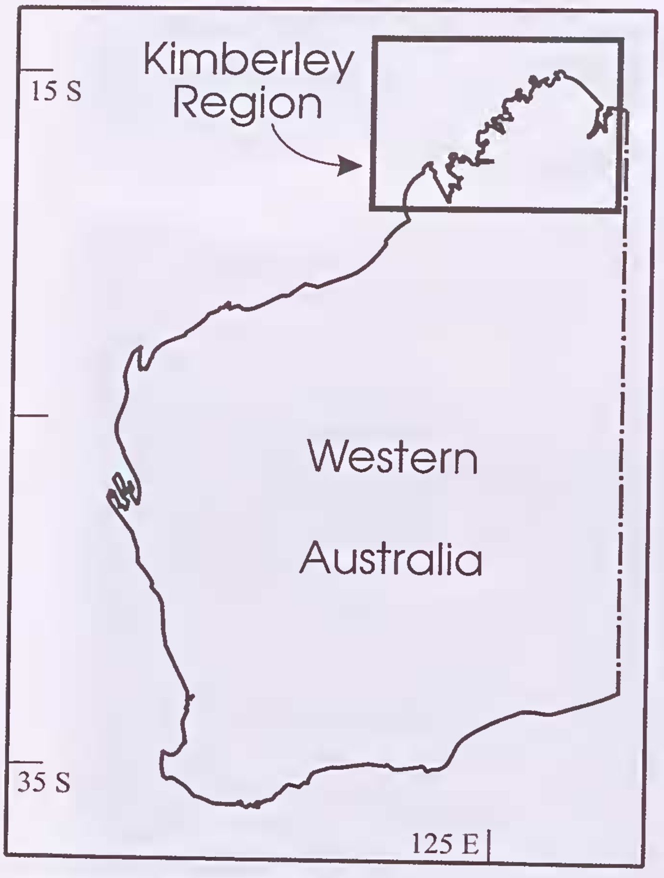

Figure 1. Location map of the study area.

considerations, the Kimberley Coast, as a rocky shore, also uniquely exhibits along hundreds of kilometres of shore extensive outcrop of Precambrian rock that indicates relative tectonic stability since the Proterozoic, and a contact along sea cliffs between a Proterozoic sedimentary basin and a Proterozoic tectonic zone (now an orogen). Additionally, the coast resides in a tropical monsoonal and generally macrotidal environment, with a strong inter-annual influence of cyclones, factors not comparable to ria coasts developed elsewhere in the world, with the consequence that coastal forms and products developed here are unique to this region. Finally, the coast is geomorphically varied in its orientation so that different parts of the coast are subject differentially to the coastal processes of tides, wind, wind-waves, swell, and cyclones such that, even though the geology is relatively simple and generally uniform from a regional perspective, there is significant sedimentary heterogeneity.

This paper is an account of the Kimberley Coast in Western Australia, with a description of the coastal forms, the reasons underpinning the development of the various coastal types, and the geoheritage significance of the coast at International and National level. However, in order to put the Kimberley Coast, as a ria coast, into geoheritage perspective, several matters are first discussed: the concept of ria coast, the theory underpinning geoheritage, the scope and scale of features of geoheritage significance, the levels of significance afforded to geoheritage sites, coastal classification in relation to geoheritage, and methods of inventory-based site-identification and assessment.

There are several ways of viewing the length of the Kimberley Coast. Using a simplified over-arching measure, it has a length of ~ 700 km. This is the measure used to compare other ria coasts elsewhere in Australia and globally. A more detailed measure involves adding the interior lengths of embayments, inlets, and large bays. From this perspective, the Kimberley Coast has a length of ~ 4000 km.

This paper is based on a combined 50 years of study in the Kimberley region by the authors. The sites described in this paper have been examined by field work, involving boat-work, land-based vehicle access, aerial surveys by fixed wing aircraft, and helicopter. All surveys were accompanied by intensive documentary photography. Additional work was carried out by desktop aerial photographic studies. On-site studies involved description of coast as to form and lithology, sampling of sediments, and determination of Quaternary stratigraphy by augering and from cliff exposures. Samplings sites, and flight paths for fixed wing aircrafts and helicopters are shown in Figure 2.

What is a ria coast?

In the literature there has been debate about what constitutes a *ria* and a *ria coast* (Johnson 1919; Cotton 1956; Fairbridge 1968b; Castaing & Guilcher 1995; Evans & Prego 2003). The term "ria" originates from the Spanish *ria* (from *rio*, or "river"). The term derives from describing the large narrow inlets on the coasts of Galicia (Fig. 3), north-western Spain (such as the Ria de Arosa and the Ria de Muros y Noya), being former valleys that were submerged by relative sea level rise due to eustatism or by submergence. Richthofen (1886) first defined a ria as a marine-inundated valley cut parallel to a regional geological strike transverse to a coast. However, to date, the term *ria* has carried with it a number of implications and misapplications. For instance, while the term carries connotations of a river valley, there are ria systems, identified globally, which are not river valleys, but inundated ridge-and-basin landforms (*e.g.*, south-west Ireland), where the geological (structural) grain is transverse to the coast (Richthofen's original definition). *Fjords* (marine-flooded glacially cut valleys) are excluded from the river valley concept of ria, yet some fjords have alternated from being glacially carved to fluvially incised. Some authors, however, include fjords where the term ria has come to mean any marine-inundated valley. The use, misapplication, extension, and strict application of the term *ria*, were discussed by Cotton (1956), separating "ria *sensu stricto*" and "ria *sensu lato*", with an argument centred on the rias of Galicia on the coast of Spain, which, though comprising the original etymology of ria, do not themselves meet the definition *sensu stricto*. More modern usage has modified the definition (see below) such that the term "ria" is now a synonym for any marine-inundated valley without any structural constraint. As marine-inundated river valleys, rias generally have a dendritic to trellis pattern, reflecting the nature of the drainage of the ancestral rivers (Fig. 3), and remain open to the sea (*e.g.*, Chesapeake Bay, United States of America; and Port Jackson, New South Wales).

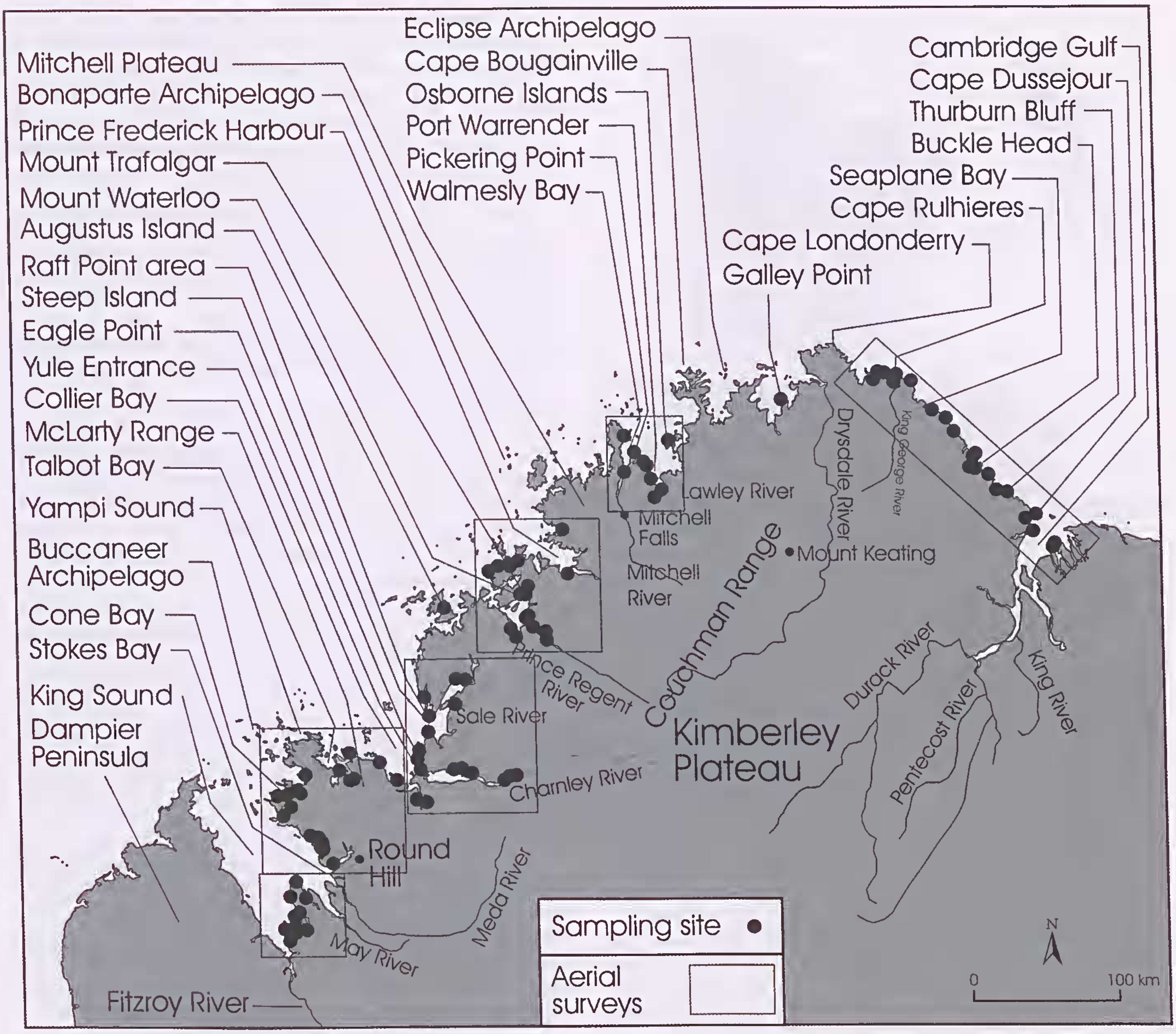

Figure 2. Sampling sites and place names mentioned in text.

Jackson (1997), drawing on a history of the use of the term, describes a ria as any long, narrow, sometimes wedge-shaped inlet or arm of the sea (but excluding a fjord) whose depth and width gradually and uniformly diminish inland, and which is produced by marine inundation due to submergence of the lower part of a narrow river valley or of an estuary. As such, it is shallower and shorter than a fjord. Jackson (1997) also notes that originally the term was restricted to inlets produced where the trend of rock structure is transverse to the coastline, but was later applied to any submerged land margin that is fluvially dissected transversely to the coastline. Less restrictively, a ria is defined as any broad or estuarine river mouth, *including* a fjord, but not necessarily an embayment, produced by partial submergence of an open valley. In this context, following Jackson (1997), a *ria coast*, building on the concept of a singe *ria*, is one having several long parallel rias extending far inland and alternating with ridge-like promontories (*e.g.*, the coasts of south-western Ireland or north-western Spain). Similarly, a ria shoreline comprises numerous rias produced by marine inundation of a land margin subaerially dissected by numerous river valleys (Johnson 1919).

Bird (2005) also provides an overview of the concepts of *rias* and *ria coasts*, and describes a ria as a long, narrow, often branching inlet formed by marine submergence of the lower parts of a river valley that had previously been incised below present sea level. Bird (2005) notes that rias are the inundated mouths of *unglaciated* valleys, usually bordered by steep slopes rising to mountains, hills, or plateaux. Clearly, fjords are excluded from the definition. There is also implication that rias are developed in a range of geomorphic settings from deeply incised valleys (*i.e.*, bordered by steep slopes) to moderately incised valleys (*i.e.*, bordered by hills). Bird (2005) cites the long, straight valley-mouth gulfs on the south-west coast of Ireland (Fig. 3) as examples of rias – these follow a geological strike that runs transverse to the general coastline (a ria according to Richthofen 1886), and notes that where rivers have cut valleys across

Figure 3. Rias from Galicia (Spain), south-western Ireland, and Sydney (NSW). Bar scale 50 km

geological structures there may be tributaries that follow the geological strike, submerged to form a trellis pattern, as in Cork Harbour in southern Ireland. Another classic example of a ria coast following the definition of Richthofen (1886) occurs along the Dalmatian coast of the Adriatic Sea where rias are elongated marine straits along valleys that follow the geological strike, linked to the sea by transverse channels.

Ria coasts around the world vary in size, shape and geology and, moreover, vary with respect to the relief of the adjoining hinterland. However, to date, no author has delineated a size limit or a size range to a ria. The type sites of rias referred to by Richthofen (1886), Cotton (1956), Bird (2005), amongst others, suggest dimensions in the order of several to tens of kilometres in length and hundreds of metres or several kilometres in width at the mouth. However, with inundation of tributaries of a river drainage system there will be decreasing size of inlets (rias) up-stream in a branching ria system. In this context, there should be no size limit to the definition of a ria, as the marine inundation of a river valley system can take place in both a highly branched system of a large river, with a wide range of valley sizes along the drainage network, or in a small river. If a smaller tributary of a large river, where marine-inundated, is considered to be part of the ria system, then an isolated marine-inundated small river should also be considered to be a ria, albeit a small ria.

As noted by Bird (2005), rias can vary in complexity of origin. For instance, the Galician rias are generally wide and deep marine inlets in valleys which may have been shaped partly by tectonic subsidence *and* the recession of bordering scarps. Subsidence has probably contributed to the persistence of the ria in the mouth of Johore River in southeastern Malaysia, which remains a wide and deep inlet, whereas other Malaysian valley mouths have been infilled as alluvial plains, some with protruding deltas. Other rias persist because they were initially deep and sedimentary filling has been slow, as along the New South Wales coast (Roy 1984). In other respects, axiomatically, ria coasts can grade into deltaic coasts, estuarine coasts, and rocky shores with indentations. There are also complications in the concept, definition, and origin of a ria where existing rias have formed by marine submergence during the Holocene transgression but, as noted above, there have been several phases of valley incision during Pleistocene low sea-level phases, alternating with earlier ria formation during interglacial marine transgressions.

Although the definition of *ria* can be broadly translated to mean "river-valley marine inlet", generally to date, it has not comprehensively and descriptively included the type and relief of the terrain that has been inundated (*cf*., review in Fairbridge 1968b). As a result, whether the marine-inundated river valley is deeply and narrowly incised (involving ravines and gorges), deeply and broadly incised, moderately incised, or bordered by a hinterland of relative low-relief, is unexplored. Thus, for example, without more refined designation as to "type of ria", or "type of ria coast", a low relief fluvially incised landscape, a moderate to high relief fluvially incised landscape, and a distributary channel system of a former abandoned Pleistocene delta, particularly if it is uplifted, strictly, would all qualify to be termed *ria coast*, and there is no current comprehensive system of descriptors or protocol to separate the types.

In the context of the review above, the coastal form of the Kimberley shores exhibit particular types of ria coast. Not consisting of isolated individual rias such as occurring along the coast of southern United Kingdom (*e.g*., Kingsbridge Estuary in England), or Chesapeake Bay in the United States of America, the Kimberley Coast presents a ria coastline, consisting of innumerable rias of various sizes, shapes, and orientations. For much of its length the Kimberley Coast is strictly a marine-inundated river-cut landscape, comprised of marine-inundated river valleys and fluvially-cut ravines of varying sizes, depths, and valley orientation, widening towards seawards. These rias are filled with sediment to varying extent. For its south-western sector, however, the Kimberley Coast is a transverse ria coast (the Irish model) where the coastal morphology is the result of inundation of a ridge-and-basin topography developed from a fold belt oriented transverse to the coast. The Kimberley Coast also exhibits marine-inundated landscapes with trellis drainage patterns, that are part of the ria suite (because they are part of the fluvial drainage network that has been marine-inundated) but that are near-landlocked embayments and narrow inlets not fully open to the sea and/or not widening to the sea as would be expected in the traditional notion of a fluvially developed ria. These rias vary in orientation from coastal-transverse, to coastal-oblique, to coastal-parallel yet all are marine-inundated interconnected fluvial valley systems. As such, the coastal landscapes of the Kimberley Coast carry the notion of what constitutes a ria coast to an extreme of its definition and presents a wide range of intergradational coastal forms of ria expression from megascale to microscale (the largest scale to small-scale), and from rias open and widening to the sea (sea-oriented in their gulf form) to those that are marine-inundated narrow (fracture-controlled) ravines to those that are near land-locked and land-oriented in their mouth. A summary of the types of rias developed along the Kimberley Coast, ranging from marine-inundated fluvially incised valleys to marine-inundated fracture valleys, will be described later to illustrate the scope of what constitutes a *ria* and a *ria coast* in this paper.

Background theory of geoheritage – scope, scale, and assessing significance

Prior to identifying and assessing sites of geoheritage significance along the Kimberley Coast, some background information is provided below, in terms of the theory underpinning geoheritage, classification of coasts to identify geodiversity of sites to assess geoheritage significance, the global approach of inventory-based site-identification and assessment, and the approach that has been designed in Western Australia to identify sites of geoheritage significance (*i.e.*, applying a Geoheritage "tool-kit").

Globally, geoheritage (the recognition of the heritage values of geological features) has become important because it has been established that Earth systems have a story to tell, and that they are linked to the ongoing history of human development, providing the resources for development, and a sense of place, and have scientific, historical, cultural, aesthetic, and religious values (Brocx & Semeniuk 2007; Brocx 2008). In addition, Earth systems are the foundation of all ecological processes, and part of the heritage of our sciences (Torfason 2001). Geoheritage and geoconservation have become a significant means for preserving geological features of importance and can range in scale from very large to fine scale, in significance from International to local, and can encompass a wide range of geological/geomorphological features, or occur in isolation, or as an inter-related suite that should be conserved as an ensemble. A Geoheritage tool kit was designed to systematically address and assess this geodiversity (Brocx & Semeniuk 2009a, 2010a).

Since geoheritage and geoconservation are concerned with heritage and conservation of matters geological, *then all components of geology should be encompassed under its umbrella.* The term geoheritage is used as follows (Brocx & Semeniuk 2007):

> *Globally, Nationally, State-wide, to local features of geology, such as its igneous, metamorphic, sedimentary, stratigraphic, structural, geochemical, mineralogic, palaeontologic, geomorphic, pedologic, and hydrologic attributes, at all scales, that are intrinsically important sites, or culturally important sites, that offer information or insights into the formation or evolution of the Earth, or into the history of science, or that can be used for research, teaching, or reference.*

The scope of geoheritage also involves identifying different categories of geoheritage significance, and all these categories can be recognised in the coastal zone (Brocx & Semeniuk 2007):

- type examples, reference sites or locations for stratigraphy, fossils, soil reference profiles, mineral sites, and geomorphic sites, including locations for teaching, research, and reference;
- cultural sites, *e.g.*, where classic locations have been described;
- geohistorical sites where there are classic exposures in cliff and outcrops where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed;
- modern, active landscapes where dynamic processes are operating.

Coastal geoheritage pertains to matters of geoheritage and geoconservation specifically in the coastal zone, an interface on the Earth's surface that is rich in geological and geomorphic processes and products because of the interaction geomorphically, sedimentologically, hydrochemically, biologically, and diagenetically, between land, sea, freshwater, and atmosphere (Brocx & Semeniuk 2009b).

Scale is important to consider in geoheritage and geoconservation because sites can range from landscapes and geological phenomena at montane-scale and orogen-scale to that of outcrops, bedding planes, or a crystal, *viz.*, megascale, macroscale, mesoscale, microscale, and leptoscale (Brocx & Semeniuk 2007). In many locations globally, geological sites are important because of crystal-sized phenomena and crystal fabrics, because it is often at this scale that the story of the Earth unfolds. At the next scale in increasing size, features of geoheritage significance, represented by outcrops and bedding scale features, include fossil sites, or Hutton's unconformity at Siccar Point (Brocx & Semeniuk 2007). Important geological and geomorphological features continue to occur in increasing scale, right up to the scale of mountain ranges, extensive landforms, and major drainage basins, such as Monument Valley Utah/Arizona, or The Grand Canyon in Arizona (Holmes 1966; Shelton 1966).

In this paper, the classification of coasts (Brocx and Semeniuk (2010b) and the Geoheritage "tool-kit" (Brocx and Semeniuk 2009, 2010a), has been used to identify and assess the geoheritage significance of the Kimberley Coast, using the descriptors for scale, *i.e.*, from megascale to leptoscale, as a means of assessing geoheritage significance, in association with criteria for levels of significance as follows::

- International: one of, or a few, or the best of a given feature globally;
- National: though globally relatively common, one of, or a few, or the best of a given feature Nationally;
- State-wide/Regionally: though globally relatively common, and occurring throughout a Nation, one of, or a few, or the best of a given feature State-wide or Regionally; and
- Local: occurring commonly through the world, as well as Nationally to Regionally, but especially important to local communities.

Coastal classification for purposes of identifying sites or features of geoheritage significance

Identifying sites or features of coastal geoheritage significance requires a number of steps beginning with classification of coastal geology and geomorphology and geoheritage category. As discussed by Brocx & Semeniuk (2010b), classifying coasts for geoheritage purposes is difficult due to the complexity, intergradation, and different scales at which coastal features are expressed, with variation potentially present locally or regionally, and with variation in expression of outcrop and cultural/historical content. While geological region and environmental setting play major roles in determining regional variation in coastal form and coastal products, or expression of geological content, coasts at the local scale commonly are expressions of a gradation of processes from (marine) inundation, to erosion, to deposition. Biogenic activity and diagenesis also play a role in forming coasts though they tend to be subdominant to the other processes. To address this geodiversity, coasts are classified by Brocx & Semeniuk (2010b) according to the products formed by the coastal marine five processes, *i.e.*, marine inundation, erosion, sedimentation, biogenesis, and diagenesis. However, some coasts are significant because they illustrate ancient geohistorical sequences, or manifest Holocene history geomorphically and stratigraphically. Twelve types of coastal forms and/or geological features developed in the coastal zone have been identified by Brocx & Semeniuk (2010b):

- Type 1 landforms developed by the post-glacial marine inundation of pre-existing landforms (the primary pre-inundated landscape is still evident)
- Type 2 landforms developed by marine inundation of pre-existing landforms and coastal erosion of the bedrock geology, or hinterland landforms
- Type 3 landforms wholly developed by coastal erosion, or where erosion has totally or nearly totally overprinted primary (pre-transgression) hinterland landforms
- Type 4 coasts developed by the exhumation or isolation of older landforms and their geological features
- Type 5 coastal landforms developed by marine inundation and sedimentary infilling
- Type 6 landforms wholly constructed by coastal sedimentary processes that have been active during the Holocene
- Type 7 landforms constructed by Holocene coastal sedimentary processes that have superimposed erosional features
- Type 8 biogenic coasts
- Type 9 coasts with dominant or conspicuous diagenetic features
- Type 10 erosional coasts recording Holocene sea-level history
- Type 11 Holocene depositional coasts recording sedimentary history, ocean history, climate history and sea-level history
- Type 12 sea cliffs exposing lithology, stratigraphic sequences and contacts, and structure

The classification of coastal types is not fixed to scale, and the various types are related to scale by a descriptor (Brocx & Semeniuk 2010b).

Identification of sites or features of geoheritage significance

There are a number of ways that sites of geoheritage significance may/can be identified. The literature provides a history of how this has been achieved, with a focus generally on significant geological features present in inland sites, or with a focus on geological content for science and education, or themes, with the final outcome being that globally, an ad hoc approach for conserving sites of geoheritage significance has been, or is being, replaced with an inventory-based approach (Doyle *et al.* 1994; Wimbledon *et al.* 1995, 2000; Wimbledon 1996; Fuertes-Gutiérrez & Fernández-Martínez 2010; for discussion see Brocx 2008). For instance, since 1949, the assessment and subsequent selection of sites in the United Kingdom has been undertaken on the basis of a series of blocks which may be based on time, subject or regional divisions, or combinations thereof. Building on this process, in 2001–2002 ProGEO contributed to a number of important geoconservation initiatives that included the incorporation of a policy statement relating to the importance of geology and physical landscapes in the Pan-European Biological and Landscape Diversity Strategy, and an alliance with the International Union of Geological Sciences and UNESCO for the purpose of compiling a European inventory for the Geosites project (ProGEO 2002a, 2002b, 2002c).

A systematic inventory-based approach to geoheritage and geoconservation requires a procedure, and identifying geological regions and what comprises the "geological essentials" of those regions provides the first step to developing such a procedure in order to identify the fundamental geological features for geoheritage/geoconservation (Brocx and Semeniuk 2010a). Clearly not all aspects of geology of the Earth are present in the one region, and clearly not all aspects of the geology of a given region will be of geoheritage significance – the former, for instance, recognises the unique occurrence, rarity, or representativeness of some geological features, and the latter requires some measure of assessment of significance.

The Geoheritage tool-kit, illustrated in Figure 4, provides the procedure to identify geological components across various geological sub-disciplines and at various scales, to assign geological sites to various conceptual categories of geoheritage, and to assess the levels of significance of the various geological features (Brocx & Semeniuk 2009; 2010a). These concepts assume that the wider definition of what constitutes 'geoheritage', as discussed in Brocx and Semeniuk (2007), is being applied. While initially developed for use in Western Australia, its principles and approach, in fact, have global applicability. The steps for identifying sites of geoheritage significance, using an inventory based approach, using the Geoheritage tool-kit are described below.

Step 1 – identify the geological region and environmental setting in which a site or feature occurs: The identification of geological regions and environmental setting provides a natural boundary to the

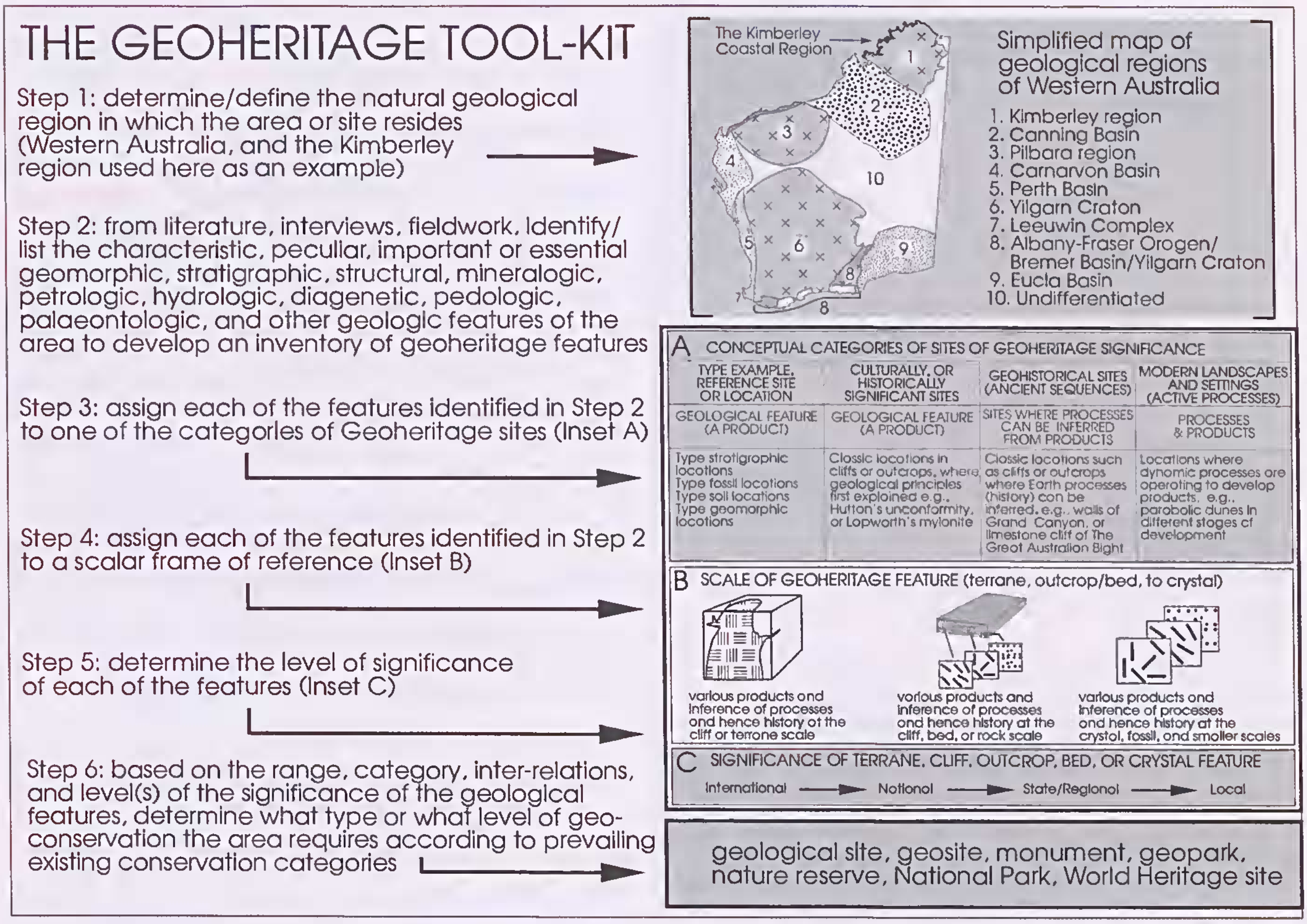

Figure 4. The Geoheritage tool-kit. Geological regions from Brocx & Semeniuk (2010b), and based on Geological Survey of Western Australia (1975, 1990), Playford *et al.* (1976) and Myers (1994).

area being investigated in terms of geological and geoheritage features, and provides an indication of the types of materials and styles of geological features and coastal features that may be expected. It also ensures that comparisons in assessing levels of significance are undertaken wholly within similar geological regions with similar history. Identifying the various geological regions, and then identifying features therein, therefore, is the first stage of a systematic inventory-based approach to developing a database for sites of geoheritage significance according to the scope placed onto geoheritage (i.e., all matters geological). This does not necessarily translate to just listing isolated sites of geoheritage significance but may also lead to the identification and linkages to interrelated ensembles of features. For Western Australia, this translates to recognising major cratons and basins cropping out at, or forming the coast, and the climatic/oceanographic setting of a coastal tract.

Step 2 – compile a list (or inventory) of features that characterise, or are peculiar to, or that are the essence of the area: Undertake literature reviews, interviews, and/or fieldwork an inventory is compiled of the geomorphic, stratigraphic, structural, petrologic, hydrologic, mineralogic, palaeontologic, diagenetic, pedogenic, and other geologic features that characterise, or are peculiar to, that are the essence of the area, or that already have been recognised as important to that region. For instance, in the Kimberley region, the Precambrian rock types, features that illustrate their structural and metamorphic history, the Cainozoic ferricrete and laterite, and the landscape as related to geology, comprise the geological essentials of that region, and on the Nullarbor Plain, the Tertiary limestone, the coastal cliffs, the karst, the cave sedimentary deposits, the late Cainozoic surficial aeolian sand sheet, and wetlands would be identified. Specifically for coastal geoheritage, this step, at the largest scale, involves classification of the coast types developed by the five main coastal processes within a given region, and, at smaller scales, involves identifying smaller scale features particular to any coast within its regional setting.

Step 3 – allocate each of the components of the list, or ensembles of the components (developed at Step 2) to a conceptual category of geoheritage: Determine whether a given location is a reference site, a cultural site, a geohistorical site, or a modern active landscape so that comparisons in assessing levels of significance are undertaken within similar conceptual categories.

Step 4 – allocate the geologic features in the list to a specific scalar frame of reference: This is so that assessments of levels of (comparative) significance can be undertaken within similar scalar categories.

Step 5 – assess the level of geoheritage significance: Use of the definitions/criteria outlined above for each of the components of the list developed at Step 2 to assess significance. The next stage would be to locate the best known examples, regardless of scale, of these features or of inter-related ensembles of features.

Step 6 – determine what type and what level of geoconservation the area requires: After an assessment of the range, categories, inter-relationships, and level(s) of significance of the geological features, determine what type and what level of geoconservation is required.

Once the inventory of components and their level of significance of a study area are compiled (in this case, the Kimberley Coast), and enough geological features have been ranked as being of significance, or a few rank as being of high significance, sites of geoheritage significance can be proposed/proffered for geoconservation at a Regional, State, National or International level for one or a few of its components, or for the integrated ensemble of its components. If the latter, the area may qualify to be viewed as a geological park.

Definition of the Kimberley Coast

The geographic term "Kimberley" has been applied generally to the region of north-western Australia to include the upland area of the Kimberley Plateau, the Kimberley coast, the area east of the Kimberley Plateau such as Cambridge Gulf and its adjoining uplands, King Sound and Stokes Bay and their bordering uplands, the Dampier Peninsula, and the area of Broome. The geographic term, administratively and politically, even has been applied to areas as far south as Eighty Mile Beach along the Canning Coast. In terms of coastal geomorphology, coastal sectors, natural coastal units, and geology, the Kimberley Coast was restricted and defined by Semeniuk (1993) to refer to the highly indented coastline bordering the Precambrian massif of the Kimberley Basin, and its bordering Precambrian King Leopold Orogen. King Sound (including Stokes Bay) and Cambridge Gulf are excluded from the definition of the Kimberley Coast, and form adjoining coastal sectors (Fig. 5). This usage of Kimberley Coast is adopted here.

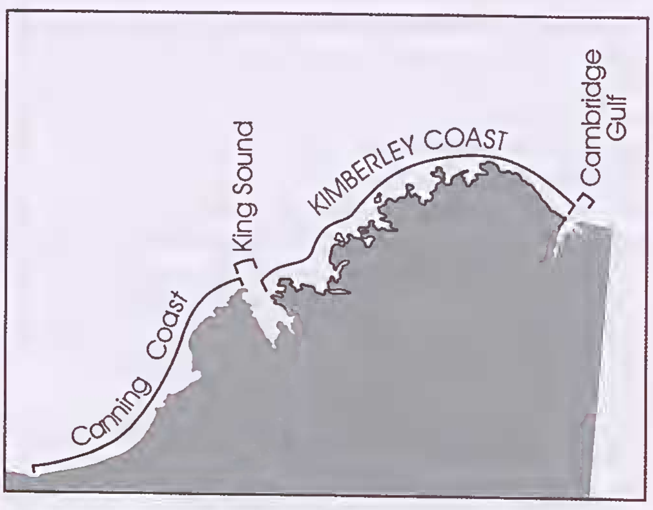

Figure 5. The location of the Kimberley Coast.

The Kimberley Coast is a rugged, dominantly rocky coastline with local sedimentary accumulations. Its coastal form is dominated by short rivers and creeks that have incised deep valleys into the regional high-relief plateau that is underlain by sandstone and basalt. The geological grain of the region, in terms of lithological trends, fold trends, faults, and boundary between the various geological units, such as between Precambrian rock massif and Phanerozoic rocks, and those within the Phanerozoic sequences, has been selectively eroded to form major valley tracts of the Fitzroy, May, and Meda Rivers and the Pentecost, Durack, and King Rivers. The southern to south-eastern margins of the Precambrian massif also has been incised by short rivers that form tributaries (deriving from the north) and deliver sediment to some of these larger rivers. As such, the complex of larger rivers that form the large gulfs are partly filled with sediments at their proximal portions, *i.e.*, King Sound, Stokes Bay, and Cambridge Gulf, with voluminous sediment delivery from their respective large drainage basins. The short rivers with smaller drainage basins, that incise and *radially* rim the Precambrian rock massif along its south-western, western, northern, north-eastern coastal margin, form the ancestral architecture of the ria shores of the Kimberley Coast (see later).

Climate, oceanography, and coastal processes of the Kimberley region

The Kimberley region is located in a tropical monsoonal climate, spanning several broad climate subregions in terms of rainfall and evaporation (Trewartha 1968; Gentill1 1972). Following Gentilli (1972), the climate is tropical subhumid in the Cambridge Gulf area and northeast Kimberley area, tropical humid in the Drysdale River to Collier Bay area, with high rainfall centred on the Port Warrender area, tropical subhumid from Collier Bay to northern King Sound, and tropical semi-arid in the King Sound area (Fig. 6). Coastal rainfall influences local freshwater seepage, the extent that saline high-tidal flats are developed, and the development of beach rock, and evaporation determines the extent that saline high-tidal salt flats are developed. Wind in the region generates local wind waves that affect shore processes, mobilises sand into dunes, driving landward ingress of parabolic dunes, and causes evaporation of high-tidal salt flats. Wind is variable regionally (Fig. 6). The hinterland climate is important in that rainfall in drainage basins of the Kimberley Plateau determines the extent of run-off into rivers and the amount of freshwater and sediment delivered to the coastal zone. In general terms, the hinterland and the drainage basins of rivers and creeks that feed the coast zone with freshwater and sediments are largely located in semi-arid to subhumid climate.

The coastal zone of the Kimberley region is subject to four main oceanographic processes: semi-diurnal tides, wind waves, prevailing swell, and cyclones (Davies 1980; Semeniuk 1993; Lough 1998; Short & Woodroffe 2009). All of these processes are influential in coastal processes but some are environmentally/geographically restricted and some, such as cyclones and wind waves, are seasonally specific. As such, oceanographic processes are variable in their coastal effects across the region.

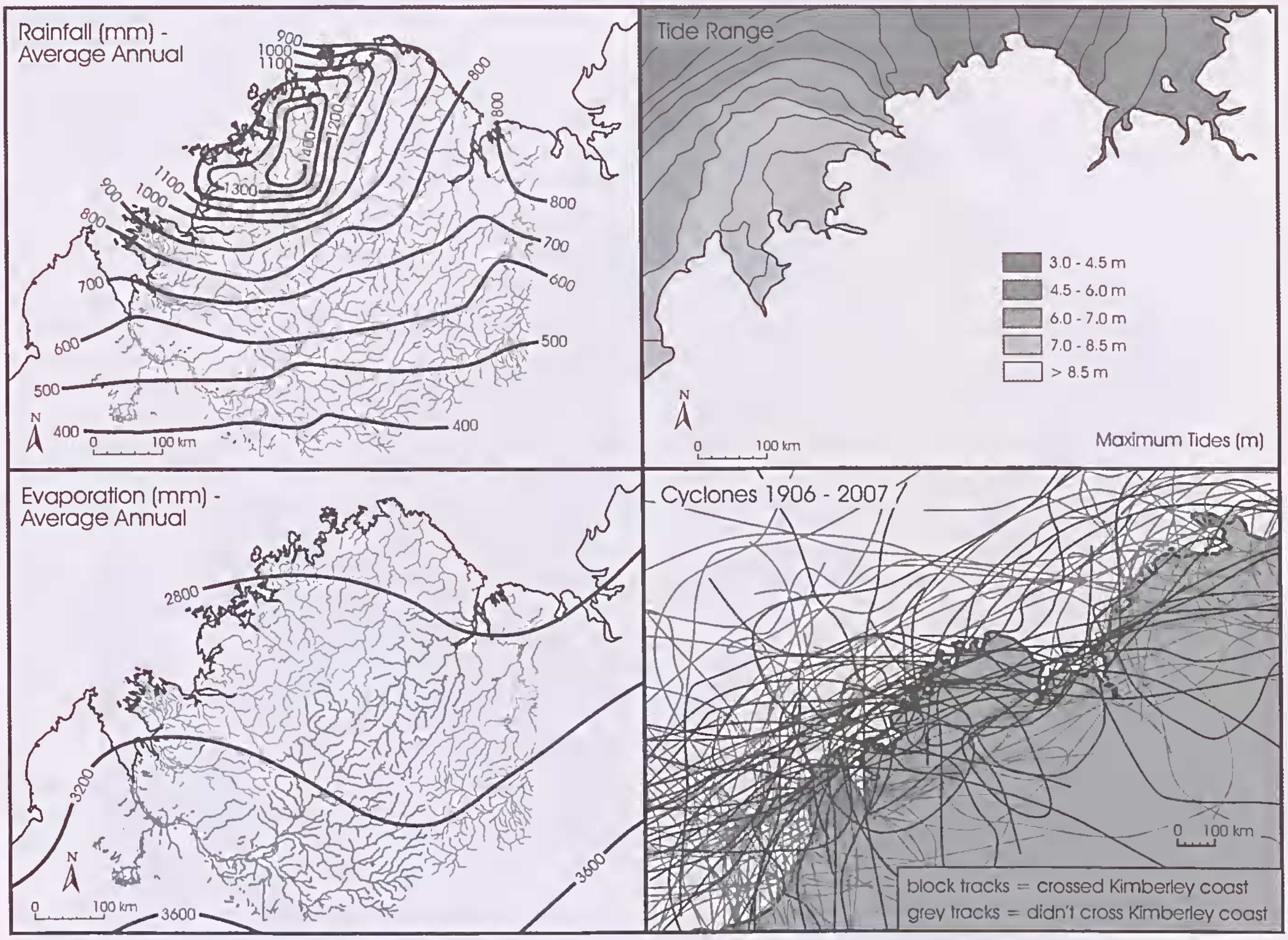

Figure 6. Rainfall, evaporation, tides, and cyclone tracks in the Kimberley region. (Climate data from Bureau of Meteorology 1973, 1975, 1988, 2010; tide data from Anon 2004). Map of average annual rainfall shows the extent of rainfall centred on the central north-western Kimberley Coast and its hinterland, and the decline in rainfall to north-east and south-west and the amount of rainfall that will recharge the drainage basins. Map of evaporation shows high evaporation across the northern coast, increasing southwards. Tide ranges are macrotidal in the area of King Sound to Prince Regent River, and Cambridge Gulf, decreasing to mesotidal in the area of Drysdale River to Cape Londonderry. The tracks of cyclone show those that intersected the coast and those that passed offshore – the former having direct impact on the coast, the latter distally generating impacts by wind, waves, and high seas.

Additionally, the shores of the Kimberley Coast are highly indented comprising south-facing, west-facing, and north-facing inlets and embayments and, in many cases, they are nearly wholly isolated from the open sea, being connected only by narrow channel-ways or waterways. As a consequence, parts of the Kimberley Coast, while subject to inundation by high tides, storm surges and cyclone-induced high-water, are protected from the action of wind waves, swell, and storm waves.

The coast of the Kimberley region is semi-diurnal macrotidal with local areas that are mesotidal (Fig. 6), and tides are a major feature of the coast in that they are pervasive regardless of its geometry, degree of shelter, and orientation (Semeniuk 2011), *e.g.*, all coastal forms from exposed sandy coves to large open embayments to narrow secluded ravines to tidal inlets and lagoons are influenced by the tide. Spatially, the next important coastal processes are wind waves and swell. Wind waves also are pervasive even in areas sheltered from swell where there is enough fetch oriented in relation to wind directions, but they are more seasonal, reflecting the seasonality of wind patterns. Wind waves are effective where coasts are relatively exposed and, depending on fetch, they have variable effects on sedimentation, coastal processes, and erosion. Hence, while wind waves are region-wide, they have most influence where headland and coves face the wind/wave direction, or where small islands act as foci for sedimentation. Swell is a year-round phenomenon, deriving from northerly to south-westerly sectors, impinging on exposed coasts that face these directions. Swell is dampened and refracted as it interacts with the shelving near-shore shelf, and it enters fracture-aligned deeply embayed rias. However, swell is not a major wave type in the region. Cyclones are inter-annual and restricted to the summer season, and highly localised in their effects on shores (Lourensz 1981; Lough 1998). They result in high seas, large waves and storm surges. During cyclone activity, there is winnowing of existing sedimentary deposits, transport and emplacement of sediments at storm levels above and well above the high tide mark, and coastal erosion. With massive influx of freshwater into the coastal zone during cyclones, there is sediment delivery from rivers/creeks to the high-tidal alluvial fans and delivery of freshwater to the coastal zone.

The geology of the Kimberley Region

The hinterland of the Kimberley Coast (*sensu* Semeniuk 1993) is a massif of Precambrian rock. Though involving *circa* 160,000 square kilometres, this Precambrian geology is relatively simple in disposition of the major rocks types and array of tectonic units. It comprises two main terranes (Griffin & Grey 1990a, 1990b; and Fig. 7): 1. the Proterozoic Kimberley Basin, which dominates the Kimberley region inland and along the coast; and 2. a semi-circumferential belt of Proterozoic folded and faulted rocks (granites and other intrusive rocks, gneisses, porphyries, metamorphic rocks, meta-sedimentary rocks, and volcanic rocks, with locally in-folded sedimentary rocks of the Kimberley Basin) referred to the King Leopold Orogen (a faulted and folded north-west trending belt bordering the south-west margin of the Kimberley Basin) and the Halls Creek Orogen (bordering the Kimberley Basin to the east).

Region-wide, five major lithological sequences of sedimentary and volcanic rocks, Proterozoic in age, accounting for a stratigraphic thickness of some 5000 m and assigned to Formational and/or Group level (as described below) comprise the stratigraphy of the Kimberley Basin (Griffin & Grey 1990b). From the base, they are: 1. the quartzose sandstones, felspathic sandstones, minor siltstones, and minor acid volcanics of the Speewah Group (1000 m thick); 2. dominantly quartz and felspathic sandstones (with local siltstone and dolomite) and basalt of the Kimberley Group (2000–4000 m thick) comprising (from the base) the King Leopold Sandstone, the Carson Volcanics (dominantly basalt), the Warton Sandstone, the Elgee Siltstone, and the Pentecost Sandstone; 3. siltstones, and sandstones of the Bastions Group (1500 m thick); 4. the Crowhurst Group; and 5. the Colombo Sandstone. Sandstone, in fact, dominates the rock sequences of the Kimberley Basin. Intrusive mainly into the Speewah Group and to some extent into the Kimberley Group is the multiple sill complex of the Hart Dolerite, with a combined thickness of 3000 m thick (Griffin *et al.* 1993). Locally in the south-western part of the Kimberley region, and specifically in the area of the King Leopold Orogen, there is outcrop of the Yampi Formation (formerly the Yampi Member of the Pentecost Sandstone; Tyler & Griffin 1993) comprised of felspathic and haematitic sandstone and minor siltstone that forms coastal terrain in the Raft Point to Yule Entrance area.

The rocks of the Kimberley Basin are largely horizontal or near-horizontal throughout the region, but they have been gently warped about on fold axes oriented in two main directions (north to north-east, and west to north-west) that are widely spaced and result in broad dome-and-basin interference structure on the scale of (25–) 50–75 km (Griffin & Grey 1990b), such that the surface geology presents several rock belts oriented NNE generally younging eastwards (Fig. 7). The major rock sequences, identified to Formational and Group level in Figure 7, thus form generally NNE-trending belts that consequently crop out at the coast in laterally extensive rock formations. The Precambrian rocks also are fractured and faulted, with some major faults and many minor faults oriented in the directions of the fractures. Faults in the Kimberley Basin trend north-west, north-east, and north, with the north-west trend having a major effect on drainage and coastal landscape. The fracture system is prominent, and is rhomboidal to orthogonal in configuration.

The rock sequences of the Kimberley Basin, as outlined above, relate to the Proterozoic rocks that underlie the entire Kimberley region, but the rock formations and lithologies *actually* cropping out at the coast are relatively more limited. In order of extent of outcrop, the main rock formations at the coast are: the King Leopold Sandstone, the Warton Sandstone, the Carson Volcanics, and the Pentecost Sandstone (Fig. 7). Thus, most of the coast is dominated by sandstone and some basalt of the Kimberley Group. Folded and faulted rocks of the King Leopold Orogen involving folded/faulted rocks of the south-western part of the Kimberley Basin and some metamorphic rocks and intrusions underpin the major coastal forms in the south-west of the Kimberley region. Though the Hart Dolerite is largely confined to inland outcrops, there is very local and minor expression of this formation at the coast. The rocks of the Speewah Group, Bastions Group, Crowhurst Group, and the Colombo Sandstone do not find (extensive) expression at the coast.

Parts of the Kimberley Plateau, and particularly where there is occurrence of basalt, are underlain by Cainozoic laterite and/or bauxite. These form resistant high-elevation plateaux and, where eroded, mesas.

A fuller account of the geology of the Kimberley Basin, King Leopold Orogen, and Halls Creek Orogen can be found in Veevers *et al.* (1970), Allen (1971), Gellatly & Sofoulis (1969, 1973), Gellatly (1971), Williams & Sofoulis (1971), Griffin (1990), Griffin & Grey (1990a, 1990b), Ruddock (2003), and Hassan (2004).

Landscape, rivers and valleys as architecture to the Kimberley coastal region

The landscape of the Kimberley region has been described by previous authors at a regional scale or at a reconnaissance level or as a background to geological studies (in the citations above), but not to any detail or emphasis for use in interpreting coastal landforms. For completeness they are cited here; they include Jutson (1950), Speck (1960), Speck *et al.* (1964), Mabbutt (1970), Jennings & Mabbutt (1977), and Pilgrim (1979).

The coastal forms in the Kimberley coastal region have been determined by the lithology and structure of regional geology, interfaces between major geological units, by marine inundation of onshore landforms, by the sizes, shapes and configuration of rivers, creeks, their tributaries, and other valley tracts in the region as controlled by the geology, and by local Holocene sedimentation such as mud accretion, and beach, spit, barrier and dune development.

Underlying patterns to hinterland landforms and to coastal forms developed from them are the horizontal nature of the dominant lithologies, the fault/fractures in the region, and the orogenic fold belt. Within the context

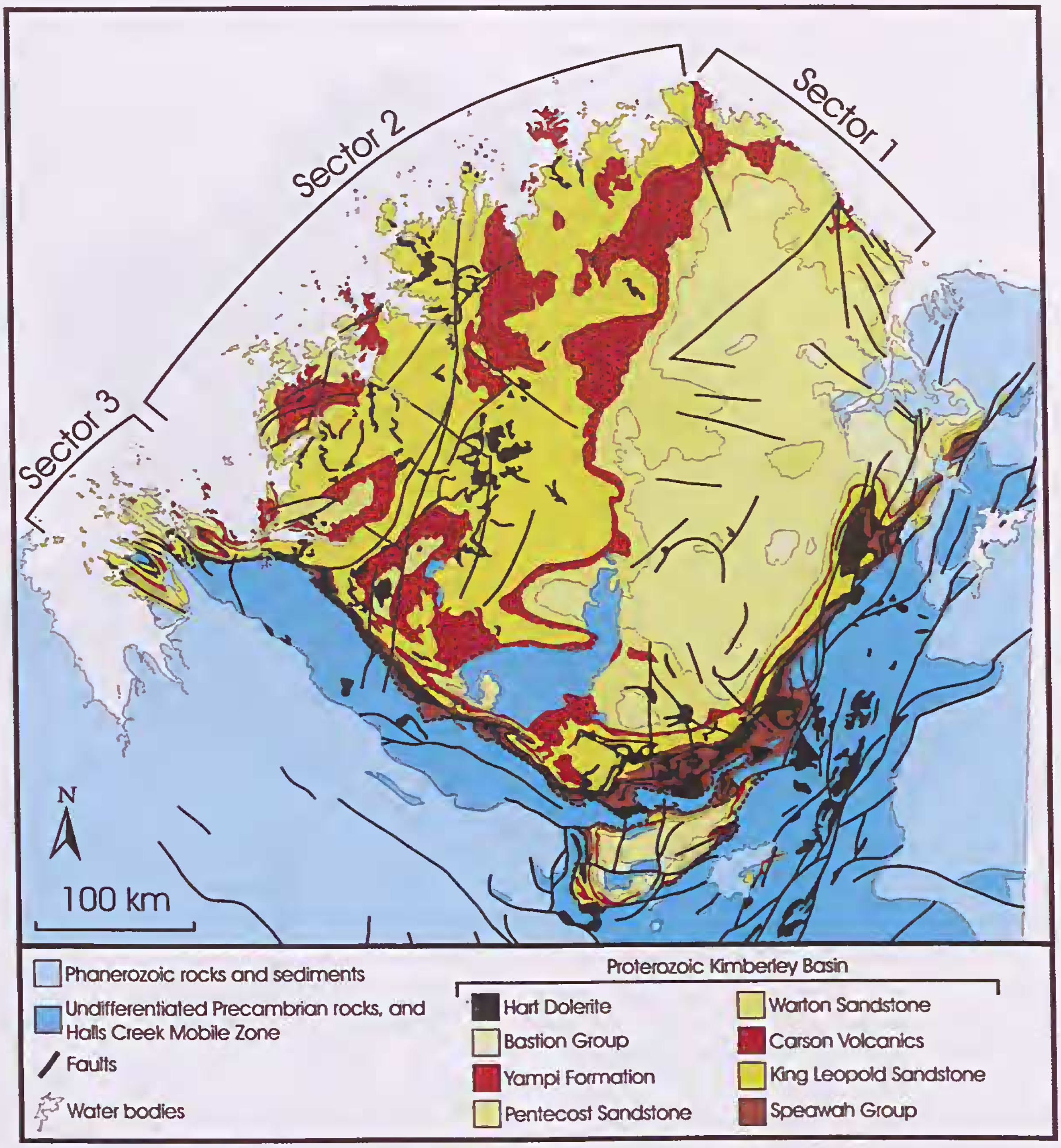

Figure 7. Geology of the Kimberley region (from Myers & Hocking 1988, with additions from Hassan 2004), and the sectors of the Kimberley Coast determined by geology.

of the sandstones and basalts that lithologically dominate the Kimberley region, structurally there are eight main determinants of landform expression of ridges, spurs, plateaux, ravines, and valleys:

1. the sandstone-dominated terrain of the inland Kimberley region, composed of relatively flay-lying lithologies, is essentially a dissected plateau with mesas;
2. the basalt-dominated terrain of the inland Kimberley region, composed of basalt, also is a dissected plateau with mesas;
3. the felspathic and haematitic sandstone terrain of the Yampi Formation, which forms a dissected. rounded topography;
4. the warp (fold) axes that have resulted in the local doming of the plateau and in west-oriented drainage and northwest to north-oriented drainage;
5. major NW-oriented faults;
6. regional rhomboidal fractures, mainly in the sandstones, and thus NW, NE oriented smaller valley and ravines;
7. the King Leopold Orogen fold belt that results in WNW-oriented ridge-and-basin topography;
8. geological/lithological contacts, and contacts between terranes, that result in NNE-oriented and N-oriented embayments.

As a result, there are a number of drainage basins deriving from the main water sheds developed in the region (Fig. 8), and drainage patterns in the Kimberley region that will determine coastal forms, the nature of

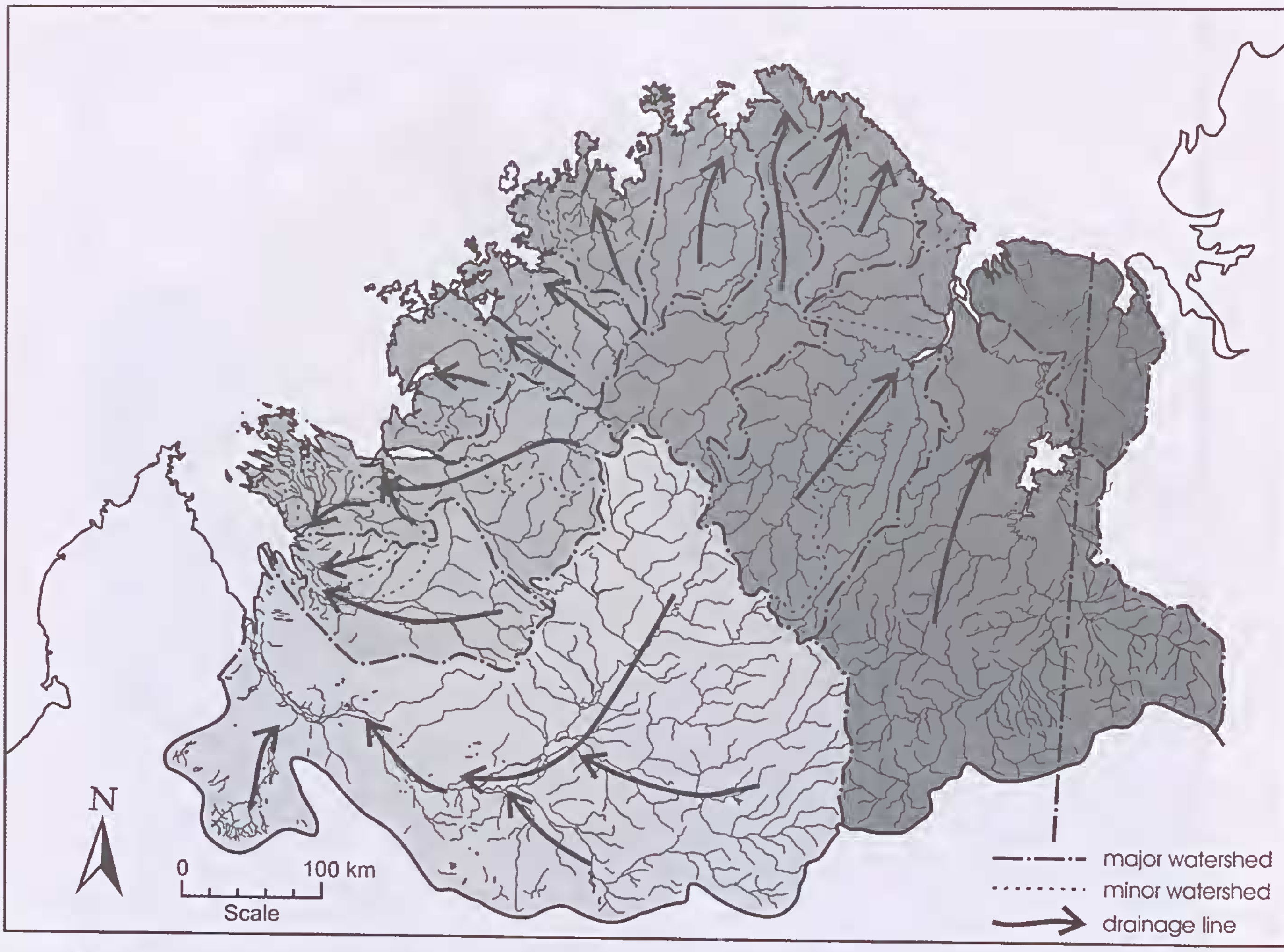

Figure 8. Kimberley region rivers and drainage basins (from Department of Water 2006).

the gulfs in the region, and the size of the drainage basins (which in turn determines the amount of sediment delivery to the coast). These drainage basin patterns are underpinned by the regional geology and structure, and by smaller scale structural features. The margins of the drainage basins define the various water sheds in the Kimberley region, and help place the size of the fluvial systems into perspective. A description of the drainage patterns is provided below. Across the region, the variability in size of drainage basin, the lithologies where the drainage basin resides, and the rainfall results in variation of sediment volumes and particles types delivered to the coast.

The drainage basins of the Durack, Pentecost, and King Rivers derive from a watershed to the west, south, and partly from the south-east. Cambridge Gulf, the confluence of these river systems, is located along the contact of Precambrian rocks and Phanerozoic rocks. The Durack, Pentecost, and King Rivers are medium-sized rivers, and the margins of their drainage basins to the west define the water shed of the Kimberley Plateau. The northern part of the Kimberley Plateau has only small watersheds and a plethora of small rivers, rivulets, creeks, and ravines following the fracture patterns of the bedrock. The north-western to western part of the Kimberley region, extending from the Drysdale River to Collier Bay, encompassing the Drysdale River, Mitchell River, and the Prince Regent River, is comprised of a series of medium rivers and small rivers that derive from water sheds centred on the Couchman Range and Mount Keating area that asymmetrically partition the Kimberley Plateau into western and eastern portions. Drainage trend semi-radially westerly to north-westerly to the coast. The south-western part of the Kimberley Coast is the marine-inundated fold-and-basin system of the King Leopold Orogen. Here, the basins form marine-inundated inlets, and also form the valleys for short rivers. The Fitzroy, Meda and May Rivers, at their distal ends, have carved out a large valley tract between the Precambrian massifs and the Phanerozoic rocks, and have also followed the faults and tectonic grain within the Phanerozoic rock sequences; they have their headwaters located in terrain developed on the folded, faulted, and fractured system of the southern margin of the Precambrian massifs, with the Fitzroy River also draining areas to the south in the McLarty Ranges.

The drainage basin systems and their seaward expression as ria coasts, together with the rocks cropping out at the coast, define three main sectors of the Kimberley Coast, (Fig. 7):

Sector 1 – the coast between Cape Dussejour and Cape Londonderry: dominated by sandstones;

Sector 2 – the coast from Cape Londonderry to Collier Bay: dominated by sandstones, but also with outcrops of basalt, siltstone, and haematitic sandstone;

Sector 3 the extension to the coast of the King Leopold orogenic fold belt.

These coastal sectors also define distinct tracts of coastline in the Kimberley region. Sector 1 is dominantly a straight coast cut mainly into Warton Sandstone, with development of small ravines, small coastal indentations, and some embayments formed by medium rivers. Sector 2 is a highly indented coast cut mainly into King Leopold Sandstone, as well as into the Carson Volcanics, Warton Sandstone and local Hart Dolerite, with development of macroscale to mesoscale embayments formed by large rivers and tide-dominated deltas and mesoscale embayments, as well as sections of straight coast with small ravines, small coastal indentations. Sector 3 is a highly indented coast formed by marine-inundation of the ridge-and-basin topography of the King Leopold Orogen comprised of a variety of folded formations (including the King Leopold Sandstone and Warton Sandstone), with development of mesoscale to macroscale embayments, as well as sections of straight coast with small ravines and coastal indentations. Local outcrops of volcanic rocks near Cape Londonderry and at Port Warrender provide smaller scale variations of coastal morphology to the any of the dominant patterns of the main sectorial patterns.

The dominating landscape feature of the onshore and coastal Kimberley region of course is the Kimberley Plateau, a terrain that is underlain mainly by fractured Precambrian sandstone with some basalt, and since the fractures and faults are prominent, they have a major influence on development of the onshore landscape and coastal geomorphology. Sandstones form a high relief plateau, with elevation of ~600 m to 300 m, falling to 200 m to 100 m at the coast. They are deeply incised by rivers and creeks, with channel margins of steep-sided ravines, bluffs, cliffs, and associated mesas. A landscape of steep-sided ravines, with bluffs and cliffs, and mesas, with variable sheer rocky surfaces, or scree, or colluvium presented at the coast, results in steep rocky shores, highly indented coastlines, bouldery shores, and nearshore or intra-ria islands (usually marine-isolated mesas). Three types of coast are developed: 1. those where the bluffs and cliffs are directly presented at the shore, thus forming steep rocky shores; 2. those where the cliffs, other high-relief landforms, and mesas are set back from the shore or have been stranded by coastal progradation, *e.g.*, Mount Trafalgar in the coastal zone of the Prince Regent River area; and 3. those comprised of a dissected plateaux and mesas thus forming ria tracts with intra-ria nearshore islands, *i.e.*, marine-isolated mesas. The cliff lines of the latter coasts are often bordered by tidal sedimentary deposits, or by aprons of colluvium, or themselves frame ribbons of sedimentary deposits.

The fluvial courses have been controlled by the faults and fracture patterns and, consequently, the valley tracts are straight, to rectangular (orthogonally) and rhomboidally branching. For instance, the Prince Regent River, a large straight river, follows a major fault/fracture, and its associated creeks and tributaries exhibit a trellis drainage pattern following the fracture patterns in the sandstone-dominated region. Many of the other rivers, creeks, and valley tracts exhibit the same geometry by following fracture patterns, exhibiting trellis drainage and criss-crossing valley tracts. In the coastal zone, where these rivers, creeks, tributaries, and valley tracts have been inundated by the post-glacial transgression, the mainland coast consists of fracture-aligned gulfs, embayments, inlets, and narrow ravines. The coastal embayments show the same style of geometry as the trellis drainage of the sandstone hinterland.

Where the Kimberley Plateau is underlain by basalt, or by felspathic and haematitic sandstone, while still exhibiting topographic elevation, the landscape and drainage are more moderate, and drainage is dendritic, with less control by fractures, and rivers, creeks, and their tributaries derive from landscapes that exhibit rounded topography. This terrain is commonly underlain by laterite which forms plateaux. Where basalt, or felspathic and haematitic sandstone front the coastal zone, the topography forms rounded coastal headlands, and broader embayments, and the rivers, creeks, tributaries, and valley tracts form more open embayments, *i.e.*, the coastal embayments show the same style of geometry as the moderate landscape and dendritic drainage of the hinterland. Where lateritic plateaux are exposed at the shore, the coast is comprised of plateau-edge cliffs backing the shore, locally with mesas forming nearshore islands or intra-ria islands. The contrast between coastal forms developed on fracture sandstone, basalt, and felspathic and haematitic sandstone is shown in Figure 9.

The King Leopold Orogen, as a tightly folded sequence of rocks, with fold axes oriented WNW and cross-cutting fractures, geomorphically forms ridge-and-basin topography of WNW-striking linear ridges (the fold limbs) and associated valleys. Minor, rivers, creeks, and their tributaries have followed the dominant grain of the geological structure, with smaller tributaries and feeder valleys following the cross-cutting fractures. Marine inundation of this topography has resulted in prominent WNW-striking peninsulae (at various scales), WNW-striking inlets, embayments, and lagoons, WNW-oriented chains of islands as small local nearshore island (archipelago) complexes (*viz.*, the Buccaneer Archipelago), isolated or near-isolated linear high-tidal marine enclosures and, where fracture has influenced cross-oriented drainage, trellis-shaped embayments and inlets.

Boundaries between major geological units, major faults and fractures, and tectonic grain, and/or a location with a geological unit, have been the control for development of some major rivers (compare Figure 7 with Figure 8). Following the post-glacial transgression, the seaward expression of the major rivers are large gulfs and inlets. As noted earlier, the Prince Regent River follows a major NW-trending fault. The Fitzroy, May and Meda Rivers have carved valley tracts following the geological strike of lower Phanerozoic rocks and, in part, the boundary between Precambrian and Phanerozoic rocks. The drainage basins of the Pentecost, Durack and King Rivers, terminating in the funnel-shaped Cambridge Gulf, have been localised in, and controlled by, the folded and faulted terrane of the Halls Creek Orogen.

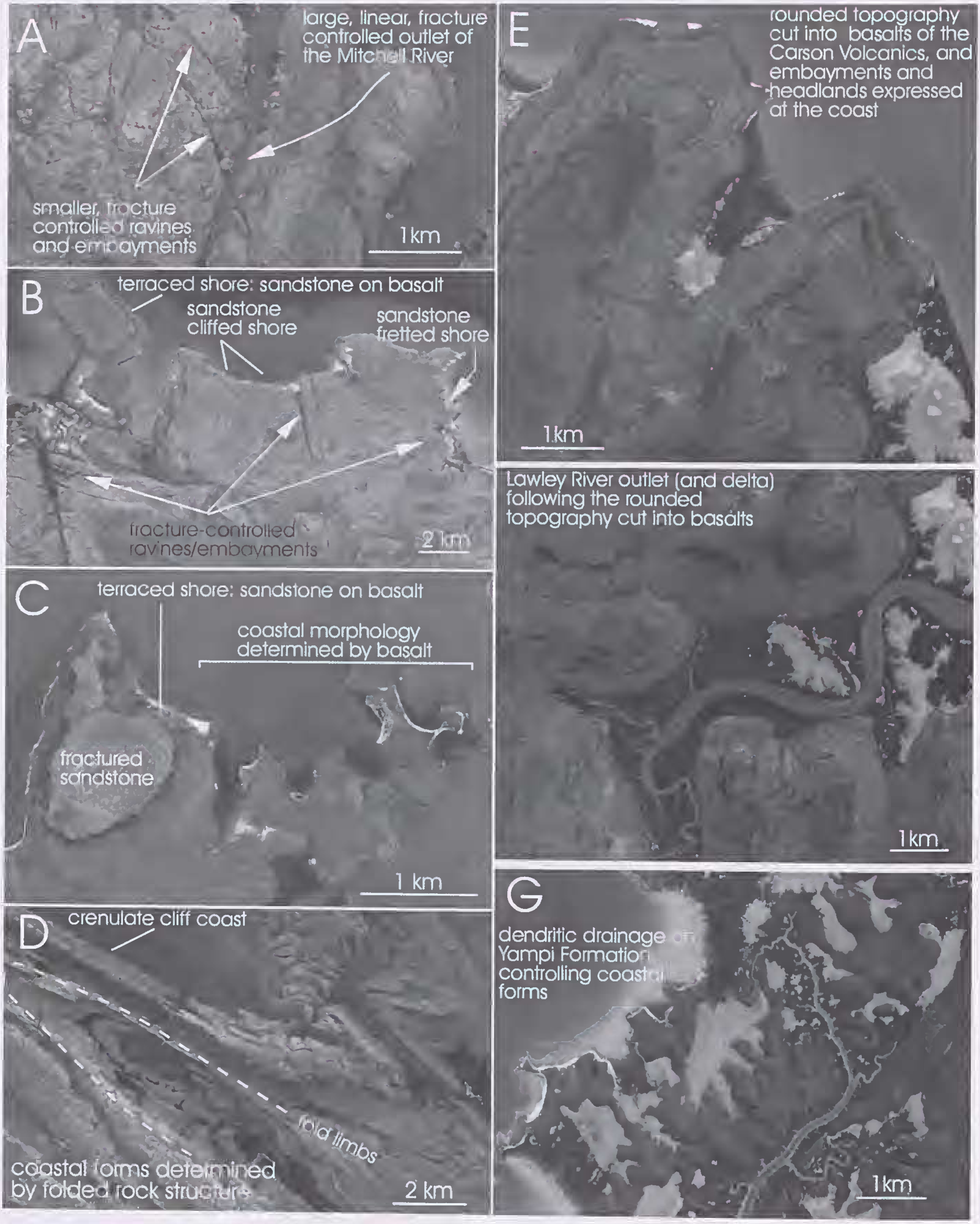

Figure 9. Annotated aerial photographs showing contrast between coastal forms developed on fractured sandstone, basalt, felspathic and haematitic sandstone, and folded rocks, with fracture-controlled ravines and embayments, and terracing controlled by the stratigraphy. Images from Google Earth.

The nature of ancestral (pre-Holocene) topography or landforms in the Kimberley region that were inundated by the post-glacial transgression to develop the modern coastal landforms, such as gulfs, embayments, inlets, archipelagos (*viz.*, the inner part of the Buccaneer Archipelago and the Bonaparte Archipelago, and the Eclipse Archipelago) and ocean-facing cliffs, is another factor that determines what landforms and what types of deposits are generated at and within the coastal zone. In other words, coastal forms along the Kimberley Coast have been determined by the nature of the onshore landforms, their underlying geology and the interfaces between major geological units, and by the sizes, shapes and configuration of rivers, creeks, their tributaries, and other valley tracts in the Kimberley region. Ancestral topography and geology also determine the size of embayments, their shape, their orientation, whether they have been fluvially derived, and whether the indented coast grades into or is adjoined by an archipelago. Since hinterland geology is dominated by sandstone plateaux, bluffs, cliffs, aprons of scree at the foot of the bluffs/cliffs, and blankets of scree covering the rocky slopes and ridges, these form the foundation to the coastal form of the Kimberley Coast.

In the context of the geology/geomorphology described above, there are eleven coastal forms occurring along the Kimberley Coast, some of which represent the types of rias in the region, ranging from marine-inundated fluvially incised valleys to marine-inundated erosional valleys, illustrating the scope of what is a *ria* and a *ria coast* in this paper; the coastal forms are:

1. Large funnel shaped gulfs
2. Large narrow v-shaped gulfs
3. Large broad embayments
4. Medium-sized to small narrow v-shaped ravines and valleys
5. Medium-sized to small embayments and coves
6. Isolated inlets and lagoons
7. Rectilinear to rhomboidal intersecting embayment/inlet complexes
8. Archipelago-and-embayment complexes bordering the Kimberley Plateau
9. Archipelago-and-inlet complexes bordering the King Leopold Orogen
10. Straight rocky shores
11. Scattered islands in an archipelago

A selection of these coastal forms are illustrated in Figure 10.

Depending on the orientation and oceanographic aspect of these coastal forms, they experience a gradation of wave and tidal energy, and hence determine or influence the nature and style of sedimentary accumulations. They may be exposed to prevailing swell and wind waves and thus subject to high energy of waves and tides. They may be relatively protected from prevailing wave action and subject mainly to tidal currents. Or they may be fully protected from wave action and only inundated on the highest tide (at times of near slack-water and slack-water) and thus oceanographically of low energy. The nature and style of sedimentary accumulations is also determined by how much sediment is delivered to or generated at the coast.

The coastal landforms, derived from marine inundation of the ancestral landforms, form the template for local Holocene sediment deposits that also contribute to coastal landform development through mud accretion on tidal flats, and beach, spit, barrier and dune development (Coastal Types 5, 6 and 7 of Brocx & Semeniuk 2010b). The sedimentary deposits along the Kimberley Coast are described by Semeniuk (2011), and a summary list is provided below. The sedimentary deposits form natural packages that are grouped into eleven suites reflecting their coastal setting, sediment types therein, processes, and stratigraphy; The simplest stratigraphic packages are ordered in a general manner from coarsest sediment and high-energy-emplaced to the most fine grained deposits, *i.e.*, from tempestites to mud tidal flat systems. The exceptions to this list, relating to energy spectrum, are the ria and embayment systems and bar-and-lagoon systems, which, as noted above, are complex ensembles of sediments. The stratigraphic packages are:

1. Tempestites
2. Block, boulder and gravel shore deposits
3. High-tidal alluvial fans
4. Tombolos and cuspate foreland deposits
5. Beach cove deposits
6. Barrier sand/gravel deposits
7. Beach-ridge deposits
8. Sand-and-mud tidal flat systems
9. Mud tidal flat systems
10. Ria and embayment systems
11. Bar-and-lagoon systems

However, Semeniuk (2011) focused only on sedimentary material in the region, and not on Holocene indurated materials along the Kimberley Coast. Geologically important, and of geoheritage significance there are three other types of Holocene coastal materials; these are:

1. Fringing algal reefs
2. Fringing coral reefs
3. Beach rock

The algal reefs are shore-fringing boundstones (term after Dunham 1962, referring to accretionary deposits of skeletal organisms that form rigid carbonate structures). The algal boundstones (reefs) are deposits that encrust rocky shores at low tidal levels. They have fringing pavements up to 100 m wide, extending seawards from the rocky shore cliff. Structurally, they are composed of grossly layered skeletal boundstones with numerous platy to irregular cavities. Biologically, they are composed mainly of calcareous algae, with scattered small corals, embedded bivalves, lithophagic bivalves, interlayered and encrusting serpulid worm tubes, other worm tubes, bryozoans, hydrozoans, and sponges. Details of these fringing algal reefs will be described in a later publication.

The fringing coral reefs also are shore-fringing boundstones that encrust rocky shores at low tidal to subtidal levels, but are coral-dominated. Coral and calcareous algae have built fringing coralline structures extending seawards from the fringing algal reefs. Structurally, they also are composed of grossly layered skeletal boundstones with numerous platy to irregular

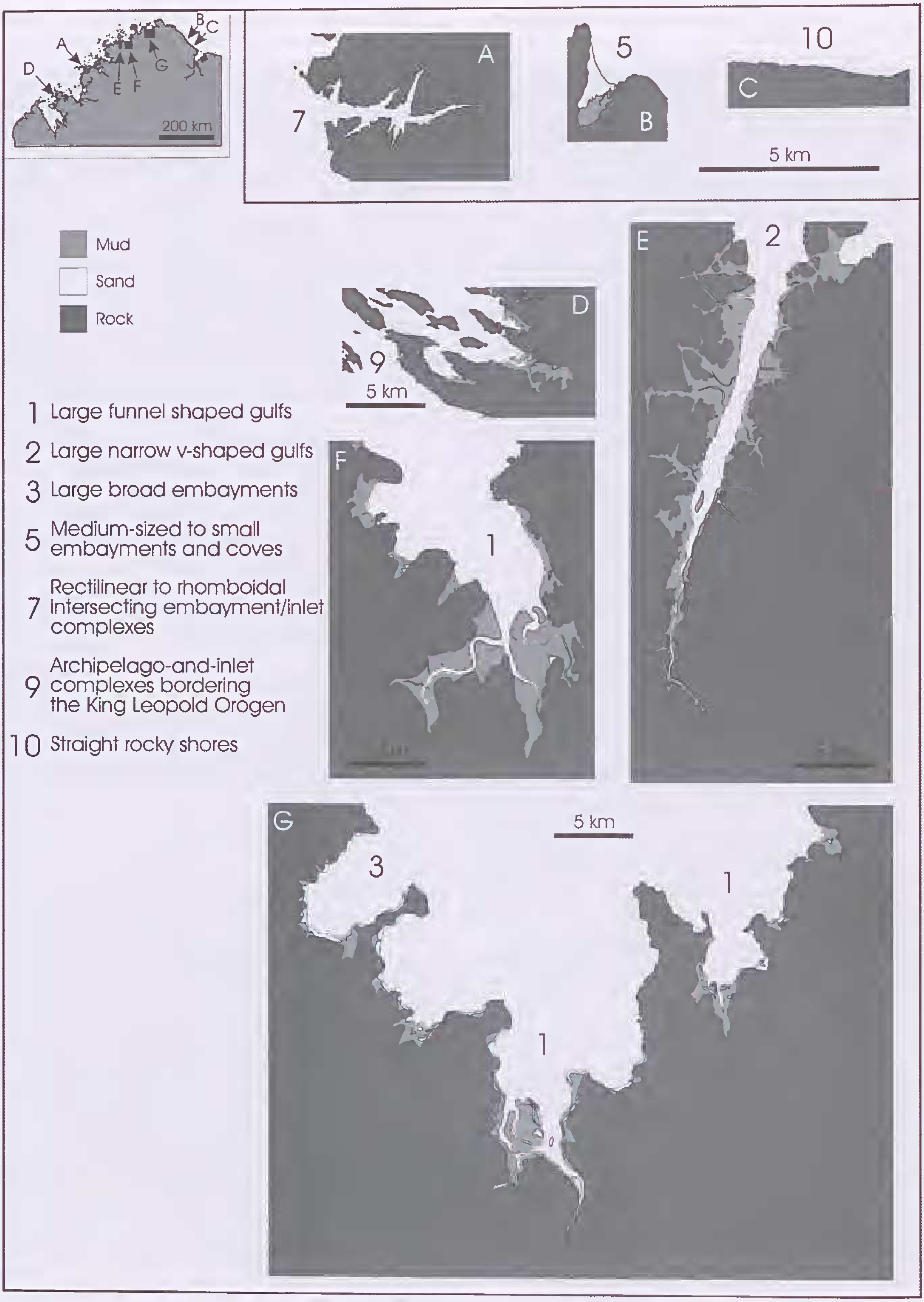

Figure 10. Major coastal forms of rias along the Kimberley Coast showing the variation in their size and shapes, annotated with the style of sedimentary deposits occurring within them. Bar scale for A, B, C, D, E, F & G is 5 km. The numbers refer to one of the eleven coastal forms mentioned in the text, and the letters A, B, C, etc. show the location of the example along the Coast.

cavities. Similar to algal reefs, biologically they are composed mainly of interlayered corals and calcareous algae, with embedded bivalves, lithophagic bivalves, and interlayered and encrusting serpulid worm tubes, other worm tubes, bryozoans, hydrozoans, and sponges.

Beach rock occurs in numerous locations along the Kimberley Coast. This is slope-parallel indurated beach sediment in the tidal zone (as sand or shelly beach sand or beach gravel), and can form beach-rock shore.

Essentials of the geoheritage features of the Kimberley Coast

The Geoheritage tool-kit has been used to identify sites or features of geoheritage significance on the Kimberley Coast, following steps 1–5 outlined earlier. Beginning with Step 1, the context for the ria coast is the Kimberley geological region and tropical macrotidal setting. The essential features are then identified and described. and their significance assessed. The assessment of the essential geoheritage features along the Kimberley Coast with respect to International, National and State-wide/ Regional significance, together with the rationale for that assessment, however, the focus is on features that are International to National in geoheritage significance. The criteria used to assign a level of significance to a geoheritage feature have been outlined earlier (following Brocx & Semeniuk 2007).

From a consideration of the geology and geomorphology of the Kimberley Coast, the features that comprise the "geoheritage essentials" of the Kimberley Coast are listed in Table 1. The key features of geology and geomorphology, at various scales from megascale to microscale, are described below with respect to their main characteristics, the category of the geoheritage site, and the scale of the feature. Given the size of Kimberley Coast, it is beyond the scope of this paper to address key coastal localities that illustrate smaller scale features such as inter-formational stratigraphic relationships and other geological relationships, any good exposures of significant lithologies or sedimentary structures, and any mineral (crystal) outcrops. The ironstones at Yampi Sound are an example of this, in that they represent, within the King Leopold Orogen, a particular style of ironstone development replete with intra-formational stratigraphic and lithological relationships, ironstone structures, and post-mineralisation metamorphism (Gellatly 1972). Identifying key localities of these ironstones along the (natural) coast, as distinct from quarry exposures, to illustrate their features of geoheritage significance in their setting of Proterozoic age and structural/metamorphic history would involve numerous sites at a scale of enquiry beyond what is presented in this paper. The same effort of identification of sites would need then to be applied to the other rock types of the King Leopold Orogen and to the sedimentary, volcanic, and intrusive rocks of the Kimberley Basin. For the latter, for instance, there are numerous locations along the coast where there are excellent exposures of sedimentary structures and conglomerate beds within the sandstones, structures within the mudstones, contacts between the sandstones and mudstones and igneous rock structures within the volcanic rocks, amongst others. For this reason, we have largely focused on the larger scale features of geoheritage significance along the Kimberley Coast, and leave the identification of the smaller scale features for a later study.

Many sites of geoheritage significance along the Kimberley Coast also have cultural significance to the Traditional Owners of the Mayala, Dambimangari, Uunguru and Balanggarra peoples, *e.g.*, coastal freshwater springs, rock formations of spiritual value, cliffs, and coastal landscapes linked to ecology. It is beyond the scope of this paper to identify such sites and, further, in terms of ethics, we do not consider that it our place as Western scientists to identify such areas within the Kimberley region. However, many of the areas assigned to specific geoheritage categories in the text below from an Earth Science point of view could also be assigned to one of Cultural Significance from the perspective of the Traditional Owners of the region.

In the list of geoheritage essentials of the Kimberley Coast, shoreline indicators of former higher sea levels (*e.g.*, stranded shore platforms) have not been included because in this rocky-shore-dominated environment there is coastal mass-wasting, breakage along the fractures of the fracture-dominated lithologies (to release slabs and blocks whose shapes are fracture-controlled) and intense erosion along open shorelines and, as such, there appears to have been continual obliteration of sea level indictors. Any indicators of former higher sea levels in high-level stranded sedimentary deposits, such as high-tidal sand platforms, similarly, have been largely obliterated by sheet wash and slope processes in this tropical setting with high rainfall in the monsoonal months. This is not to say that indicators of former higher sea levels indicators will not be found, but they have been excluded from the list of geoheritage essentials of the Kimberley Coast because they are absent in many localities, or their occurrence is ambiguous in other sites.

Generally, locations for type sections or reference sections for stratigraphic units are listed in the geoheritage essentials of a given area (Brocx & Semeniuk

Table 1

Geoheritage essentials of the Kimberley Coast
i.e., features of geoheritage significance

The extent that a ria coast is developed
Types of rias developed as related to geology
Types of rias developed at different scales
Precambrian geology: geology, stratigraphy, transition of basin to orogen
Geomorphology expressed at the coast
Biogenic coasts (algal and coral reefs)
Tempestites
Barrier sand/gravel deposits
Bar-and-lagoon deposits
Sedimentary sequences
Freshwater seepage and waterfalls
Key hydrodynamic features
Types of cliffs along rias and rocky shore geomorphology
Processes of cliff erosion
Salt weathering
Types of coasts
Diagenetic coasts
Key coastal outcrops
Scenic vistas

2010a), but these tend to be of State-wide importance and are not addressed further as this paper focuses on geoheritage features of International and National significance. Some features of State-wide significance are listed here because they are of National to State-wide importance and are described because at one extreme they can be of National significance and not solely of State-wide significance.

High on the list of features of geoheritage significance (Table 1) is the extent that ria shores are developed along the Kimberley Coast. This is because, while there are other ria coasts elsewhere in Australia and globally (as noted in the review earlier), the ria coast of the Kimberley region is globally an outstanding system in terms of its size and extent, its style of development, and its variability of geomorphic, stratigraphic, hydrological, hydrochemical, and diagenetic features.

Illustrations of coastal forms and coastal features of the Kimberley Coast are shown in Figure 11. Description and assessment of the essential geoheritage components of the Kimberley Coast are presented below.

The ria coast developed along the Kimberley Coast is a megascale feature, assigned to the geoheritage category of modern landscapes and setting (active processes). The Kimberly Coast is the largest ria coast in the World, with an overall length of some 700 km, but unlike other ria coasts developed globally, this coast is cut into resistant Precambrian sandstone, with development of steep cliffs and shoreline bluffs. As such, it is a global classroom, with International significance. The different types of rias developed along the Kimberley Coast, as related to geology, generally are megascale to macroscale features, also assigned to the geoheritage category of modern landscapes and setting (active processes). Within this single region, with (interrelated) geology of Precambrian basin to orogen, the Kimberly Coast presents a globally unique transverse coast where the King Leopold Orogen, comprising multiple lithologies, tight folds, faults, and fractures, all oriented transverse to the coast, crops out along the shore and, additionally, presents an adjoining coastal sector of marine-inundated fluvially-incised terrain. Unlike transverse coasts elsewhere globally (*e.g.*, south-western Ireland), the transverse coast in the Kimberley region is developed on Precambrian folded rock. As described earlier, these tightly folded rocks are the foundation to a (pre-Holocene) ancestral ridge-and-basin geomorphology that, when inundated by the post-glacial marine transgression, has developed coastal landforms reflecting the orientation of the ridge-and-basin geomorphology, *viz.*, ridges, spurs, razorback ridges, oriented narrow inlets, nearly isolated inlets, amongst others. The coastal landscapes themselves are globally unique in terms of their foundation geology, coastal landforms developed, styles of cliffs developed on various lithologies and various structural attitudes, and the large range of scales at which the coastal features are developed.

There are two classic ria forms which, in the literature, have been assigned type locations in disparate areas (*viz.*, transverse rias in the Adriatic Sea and south-western Ireland, and the marine inundated river valleys in north-western Spain). However, in the Kimberley region, both of these ria forms occur adjoin each other, and further occur within the same general oceanographic setting, with similar coastal processes, within a generally similar tropical climate, and a within a generally similar geology. This is a feature of International significance and, ideally, the Kimberley Coast, comprising coastal forms developed on the Kimberley Basin and King Leopold Orogen *should be viewed as the global type location for ria shores.*

There is another aspect to the types of rias along the Kimberley Coast, and that is the matter of the variety of (river valley) rias developed at different scales. The Kimberly Coast presents a range of ria coast sizes and shapes, some that are fracture-and-fault controlled, varying from large gulfs to small embayments to small ravines, with orientations that reflect the conjugate fault-and-fracture patterns of the region that resulted from the weathering/erosion of the sandstone bedrock, and some that are inundated, rounded hills and undulating terrain that resulted from the weathering/erosion of basaltic bedrock. This aspect of ria shores generally is a megascale to macroscale feature, and is also assigned to the geoheritage category of modern landscapes and setting (active processes). With its expression of marine-inundated rivers, creeks, valley tracts, and ravines of various sizes as ria coasts (since all these marine-inundated valley forms are naturally inter-gradational and form an integrated network), the Kimberley Coast provides a standard of the range of shorelines in terms of shape, sizes, and coastal orientation, that can be assigned to ria coasts and, again, can be viewed as a global classroom. It is a feature is of International significance.

The exposure of Precambrian geology along the coast is another important matter in the region. This aspect of the Kimberley Coast is a megascale to macroscale feature, and is assigned to the geoheritage category of geohistorical site. The Kimberley Coast presents well-exposed and extensive coastal cliff outcrops of Precambrian geology, that for over 700 km of general coastal length, and ~ 4000 km of more detailed measured coastal length, exhibit along the shore the sedimentary rocks and facies changes within the Kimberley Basin, volcanic rocks of the Kimberley Basin, as well as the structures and lithology of the King Leopold Orogen, and the geological transition from rocks of the mobile zone (King Leopold Orogen) to those of the Kimberley Basin. This excellent exposure and extent of exposure is a feature of International significance.

The geomorphology expressed at the coast is another important aspect of the region. The landscapes developed at the coast are partly due to the processes of coastal erosion and partly due to inundation of ancestral landforms. As such, fronting the sea, bordering the gulfs, framing the narrow inlets, or forming local islands, there are geomorphic features of sandstone cliffs, cliffs with boulder and scree aprons, plunging basaltic cliffs, bluffs, other types of steep shores, coastally-located mesas, fretted coasts, two-layered and terraced islands and cliffs, and lithologically determined platforms. Edwards (1958) first recognised lithologically determined platforms as coastal features in the Kimberley region along the shores of Yampi Sound in The Buccaneer Archipelago. Many of these geomorphic features are best expressed along extensive coastal tracts involving several to tens of kilometres of coast and should be viewed as an ensemble of coastal forms along a single large coastal tract, rather than as site-specific localities. The various forms of geomorphic expression along the coast broadly conform to the three sectors of the Kimberley Coast. For example, the coastal tract of sea cliffs between Cape Dussejour and Cape Londonderry, Sector 1, shows an overall straight coast with fracture-controlled mesoscale to microscale ravines and indentations, and lithological control of coastal cliffs and benches, and is a particular type of coast specific to this region. The coast of Collier Bay, Yampi sound, and the Buccaneer Archipelago, Sector 3, shows a highly indented form corresponding to the seaward expression of the ridge-and-basin topography of the King Leopold Orogen. In Sector 3, because of the variable lithology and the structural attitude of the fold limbs, there are various coastal forms developed: rias grading to nearshore islands and rocky reefs and archipelagos; the southern shore of Collier Bay (16° 15' 24" S 124° 0' 20" E) showing a highly indented mesoscale to microscale ria complex dominating the coast; the central north-west trending bay-dissecting peninsula (16° 21' 36" S 123° 56' 33" E) of Talbot Bay showing a crenulate northern coast; the south-western shore of Cone Bay (16° 29' 14" S 123° 30' 8" E) showing an extensive shoreline developed by steeply dipping rocks, oblique shears, and cross-fractures; and Round Hill area, northern Stokes Bay showing the contact between salt flats and rocky shore.

Some of the key geomorphic features along the Kimberley Coast illustrate examples of coastal forms that are particular to the Kimberley region. These include: partially sediment-filled embayment and digitate spur complex around Cape Dussejour; the bar-and-lagoon system between Cape Dussejour and Thurburn Bluff; the narrow v-shaped ravines formed by the bedrock fracture system 10 km south-west of Buckle Head; the two-layered, terraced cliffs formed by the Carson Volcanics and the Warton Sandstone cropping out at the coast in superposition (at Buckle Head, and 5 km NW of Seaplane Bay between Cape Dussejour and Cape Londonderry); Cape Bougainville (a highly dendritic/digitate ria coastal form with bauxite-capped plateau forming the shore and hinterland); the tide-dominated mud delta of the Lawley River; the tide-dominated sand-and-mud delta of the Drysdale River, with its ocean-facing cheniers and spits, the ria coast embayment complex of broad embayments and headland spits of Port Warrender; the peninsula of Pickering Point, the west coast peninsula of Walmesly Bay, and Bigge Island and the adjoining mainland as sites where there are rhomboidal, narrow v-shaped inlet systems formed by erosion of the bedrock fractures; the Mitchell Falls in the Mitchell River area where a riverine waterfall directly contacts with the marine environment at the head of the Mitchell River; the Prince Regent River coast with St Georges Basin and Mount Trafalgar as a large mesa bordering the Prince Regent River coastal complex; the coastal landscape of Prince Frederick Harbour in the Buccaneer Archipelago, featuring a "rock tombolo" attached to a mesa and separating/sheltering a large mangrove-vegetated tidal flat, the Talbot Bay ria system (the linear array of islands and peninsulae of the marine-inundated ridge-and-basin system of the rocks of the King Leopold Orogen).

Generally, the key geomorphic features are megascale to macroscale features, and locally microscale features, and are assigned to the geoheritage category of modern landscapes and setting (active processes) and partly to geohistorical site, the former because it is extant and still being formed, the latter because some of the landforms are ancestral and manifest pre-Holocene morphology. They are of International to National to State-wide significance from the perspective of geomorphology and from the perspective of scenic vistas (see later).

Algal reefs have been documented elsewhere in the World but they are of different types and in different settings to those of the Kimberley Coast. For instance, in the Bermuda Platform, which is dominantly a coral reef environment, they form "cup reefs" that are isolated algal bioherms with depressed centres and raised rims (James 1983), and in the Caribbean region generally they occur as "algal ridges" associated with coral reefs (Adey 1978; Tucker & Wright 1990; Bosence 1983a). Modern algal ridges and reefs composed of crustose algal frameworks (as distinct from concentrically encusting rhodolith or rhodoid accumulations; Bosence 1983b, 1983c) have been described from the "coralligène" (in the Mediterranean), at St Croix (Virgin Islands, Carribean), and the Pacific reefs, and branching frameworks have been described and illustrated from the maerl of the north-east Atlantic (Bosence 1983a). Many of the algal reefs are closely associated as a subfacies of coral reef complexes. The algal reefs of the Kimberley Coast stand distinct as being a fringing algal reef type that inhabits sandstone and basalt rocky shores, forming shore parallel platforms/ wedges, and further, these algal reefs are a phylogentically complex biocoenosis of algae and encrusting and lithophagic invertebrate fauna, rather than an accreted aggregation of crustose algae. Basso *et al*. (2009) document algal rhodoliths on rocky shores of subtropical New Zealand but these are dominantly concentrically encusting pisoliths and fruticose forms.

The biogenic coasts in the Kimberley region are mesoscale to microscale features, and are assigned to the geoheritage category of modern landscapes and setting (active processes) and partly to geohistorical site, the former because it is extant and still forming, the latter because there are earlier (Holocene) fossil forms buried in the stratigraphy of the deposits. While the algal reefs often form shore-fringing platforms along portions of the Kimberly Coast, their association with a narrow seaward periphery of coral biolithite is particularly important. Because algal reefs are globally uncommon as rocky shore fringing structures, the Kimberley Coast examples are Internationally significant. Bosence (1983c), for instance, illustrates algal reefs along rocky shores, as distinct from coral reef settings, only in few locations globally (*viz*., along the east coast of temperate climate Canada) and none in the tropical regions of the World.

Similarly, the various types of tempestites in the region, features of mesoscale to microscale size, and assigned to the geoheritage category of modern landscapes and setting (active processes), are of International significance as modern sedimentary models of tropical zone deposits formed in a cyclone-influenced macrotidal coast where corals, shell gravel, reworked beach rock slabs, and local rocky shore derivatives form the source material.

The barrier sand/gravel deposits in the region, especially the lithoclast gravel barriers, are mesoscale to microscale features that are assigned to the geoheritage category of modern landscapes and setting (active processes). Gravel barriers (and gravelly shores) occur

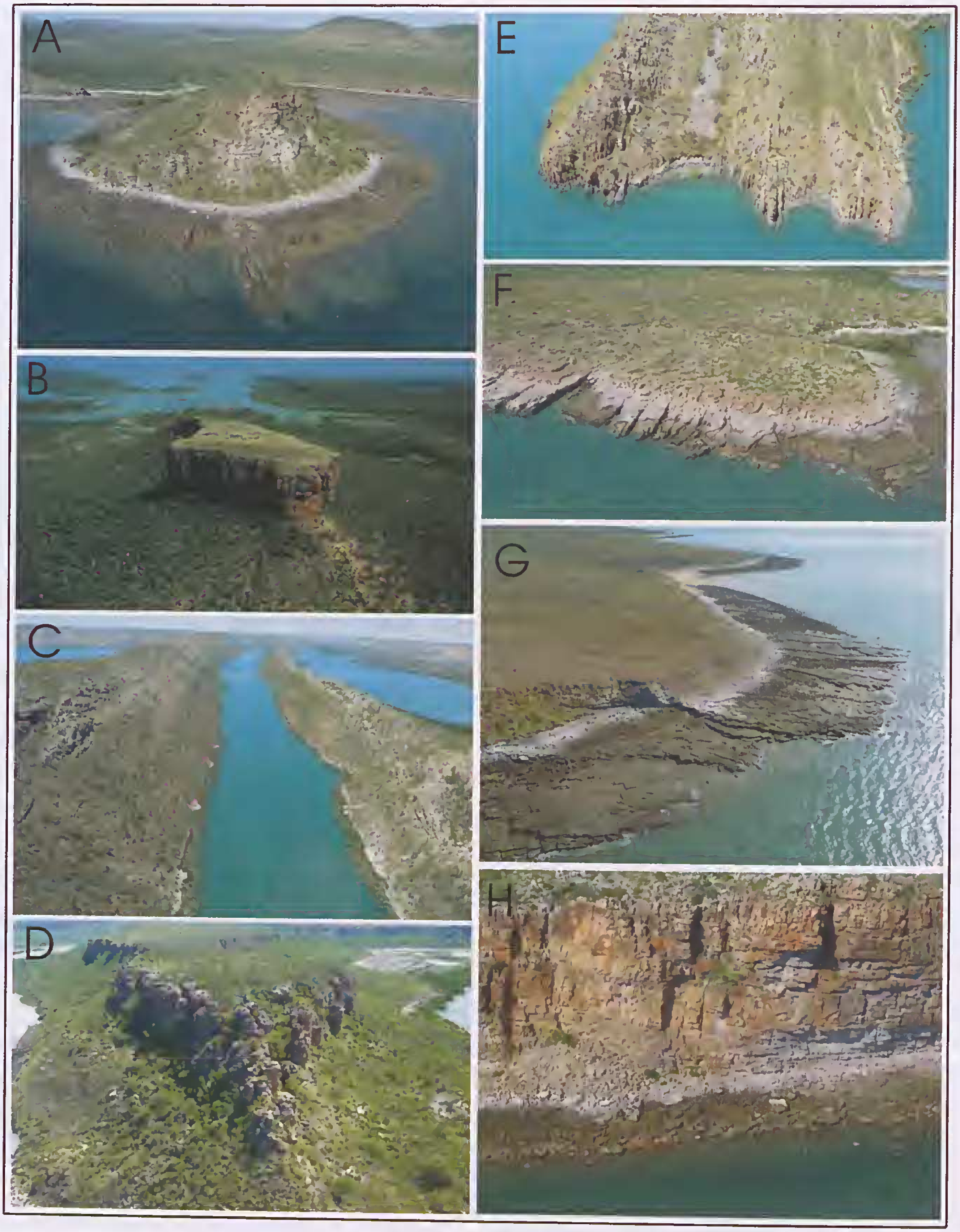

Figure 11. Oblique aerial photographs showing geomorphic features of the Kimberley Coast. A. Typical coastal form in the Kimberley region – an island of eroding jointed sandstone with scree slopes, a tidal/subtidal zone of jointed rocks and veneer of gravel, and a high-tidal to supratidal zone of (bleached) wave-reworked gravel. B. Mt. Trafalgar, a laterite-capped mesa in the Prince Regent River area, showing the nature of landforms that occur at the coast (image courtesy of Yann Arthus-Bertrand). C. Marine inundated ridge-and-basin topography (fold limbs) typical of the Buccaneer Archipelago. D. Spine of sandstone projecting as a peninsula into the sea. E. Crenulate shore formed by vertical sandstone strata. F. Crenulate shore formed by fractures and joints in sandstone. G. Sloping rocky shore formed by low angled inclined strata, with shoreline rubble boulders/cobbles. H. Bouldery shore formed by eroding jointed and bedded sandstone.

Figure 11 (cont.). I. Biogenic shore – algal biolithite fringing a sandstone shore and bouldery shore. J. Biogenic shore – algal biolithite fringing a basalt shore. K. Bar-and-lagoon system, with a sandy barrier. L. Bar-and-lagoon system, with a gravelly barrier. M. Mouth of the Berkley River delta with wave-generated sand ridges. N. Narrow ravine cut into sandstone, and a sandy barrier. O. Tempestite – blocks of sandstone perched on a structural platform of sandstone; cliff of sandstone in far-ground. P. Salt weathering forming a high-tidal pavement on dolerite.

throughout the globe but are associated most commonly with formerly glaciated regions, tectonic coasts where streams deliver gravel to the shore, and wave- dominated rocky shores (Carter 1988; Carter & Orford 1993), *e.g.*, Chesil Bank barring The Fleet (Carr & Blackley 1973), and Haslemere Barrier, both in England. However, the gravel barriers of the Kimberley Coast are specifically formed across narrow ravines cut into Precambrian rock in a tropical macrotidal setting or are reworked scree deposits (where they front the coast) and, as such, are globally uncommon and Internationally significant.

The bar-and-lagoon deposits, especially where the barriers are formed across narrow ravines, are globally uncommon. Essentially, along the Kimberley Coast, the development of bar-and-lagoon systems in a setting of a tropical climate, macrotidal regime, and cyclone influence coast, barriers formed across narrow ravines and embayments cut into Precambrian rock are Internationally significant. These features are mesoscale to microscale, and assigned to the geoheritage category of modern landscapes and setting (active processes).

The ensemble of sedimentary sequences along the Kimberley Coast, located in gulfs, tide-dominated deltas, rias, and other sedimentary settings, range from cyclone-generated tempestites, to mud-dominated systems. Their associated stratigraphic packages, developed by macrotidal and tropical conditions represent a global classroom that shows inter-relationship of morphology, and oceanographic factors such as tide-dominated or wave-dominated prevailing conditions, or cyclone generated conditions, sediment delivery, the dominance of gravel *versus* sand *versus* mud and, as such, are Internationally significant. These sedimentary sequences are megascale to mesoscale features along the Kimberley Coast, and are assigned to the geoheritage category of modern landscapes and setting (active processes).

Freshwater seepages discharging into the high-tidal coastal zone, into scree developed along the interface between basalt and sandstone, and as waterfalls (*e.g.*, the King George River cliffs, Mitchell River, and Crocodile Creek, Buccaneer Archipelago) are widespread throughout the Kimberley Coast. They are mesoscale to microscale features, and are assigned to the geoheritage category of modern landscapes and setting (active processes). The fractured bedrock of the inland Precambrian system functions as a major freshwater aquifer which discharges freshwater into the high-tidal environment, influencing diagenetic and ecological processes (the latter, specifically for mangroves). Commonly, such discharges are along the upper edge of a salt flat at its contact with rocky cliffs, but locally they appear within the salt flat. For mangrove systems (Semeniuk 1983, 1985), in a tropical ria coastal setting, this style and extent of freshwater seepage is a rare hydrological feature and is Internationally significant as a global classroom. Freshwater discharging into scree along the interface between basalt and sandstone are Nationally significant features. Freshwater discharging from rivers, creeks, and rivulets, as waterfalls directly into the sea are Nationally significant features.

The Kimberley Coast also exhibits some key hydrodynamic aspects, such as the "horizontal waterfalls". The "horizontal waterfalls" is a local area (Talbot Bay) within the ria complex of narrow inlets, parallel inlets, and serial narrow gaps cut into rocky ridges, developed on the King Leopold Orogen, in a macrotidal regime, where there is a lag of tidal water interchange between two parallel inlets and the open ocean developing water level differences of several metres across the gaps. This is an extraordinary tidal hydrodynamic feature because of the configuration of the ria shores and inlets, and is Internationally significant. The "horizontal waterfalls", is a microscale feature, and is assigned to the geoheritage category of modern landscapes and waterscapes (active processes).

While there has been emphasis in this paper on ria form and types of rias along the Kimberley coast, another important aspect of this setting is the types of cliffs along rias and rocky shores. There are, in fact, a variety of cliff types developed along the ria coast and rocky shores, the coastal geomorphology reflecting oceanographic processes, rock type, stratigraphic sequence, geological structure (*viz.*, structural attitude), and the induration, weathered nature and coherence of the bedrock. For instance, exposure of the Precambrian rock sequence to wave, tidal and cyclone activity, and salt weathering in a tropical climate, results in a variety of shore types cut into the rock, and different structurally-oriented rocks that result in plunging shores, rounded plunging shores, terraced shores, razor-back shores, "fretted" shores, "fretted" rock platforms, (vertical) cliff shores, platform-and-cliff shores, bouldery shores (with either rounded boulders, or rock slabs), rocky shores with cobble and pebble veneers (with rounded cobbles/pebbles, or platey cobbles/pebbles), and high-tidal platforms developed by salt-weathering. The range of rocky shores in this region results from the fact that the Kimberley Coast is so laterally extensive, and there is opportunity for a variety of Precambrian rock (of varying lithology and structural attitudes) to be exposed locally to the range of oceanographic processes in a generally similar climatic setting. This is a situation that does not occur elsewhere in Australia. For instance, the Tertiary limestones of the Eucla Basin, exposed in cliffs along the coastal edge of the Nullarbor Plain, though a laterally extensive cliff-line, presents a limited lithology, all in a horizontal structural attitude. Further, the Tertiary limestones are oriented parallel to latitude and front a wave-dominated microtidal ocean of relatively uniform processes which then generates a regionally relatively uniform coast type. Elsewhere the coast of Australia is too heterogeneous lithologically, *i.e.*, without the relatively consistent bedrock, to express the coastal variability of cliff lines that might develop across smaller scale changing oceanographic conditions such as the Kimberley Coast. Examples of the variety of the cliff types along the Kimberley Coast are illustrated in Figure 12. The suite of rocky shore products, illustrating geomorphology and coastal form along the Kimberley Coast, show how coastal form is expressed in laterally variable cliffs and rocky shores and is a Nationally significant classroom for rocky shore geomorphology. The rocky shore geomorphology and features range in size from mesoscale to microscale and leptoscale. They are assigned to the geoheritage category of modern landscapes and setting (active processes).

The processes of cliff erosion along the Kimberley Coast also contribute to the significance of the area. The erosional style is specific to this region because of the

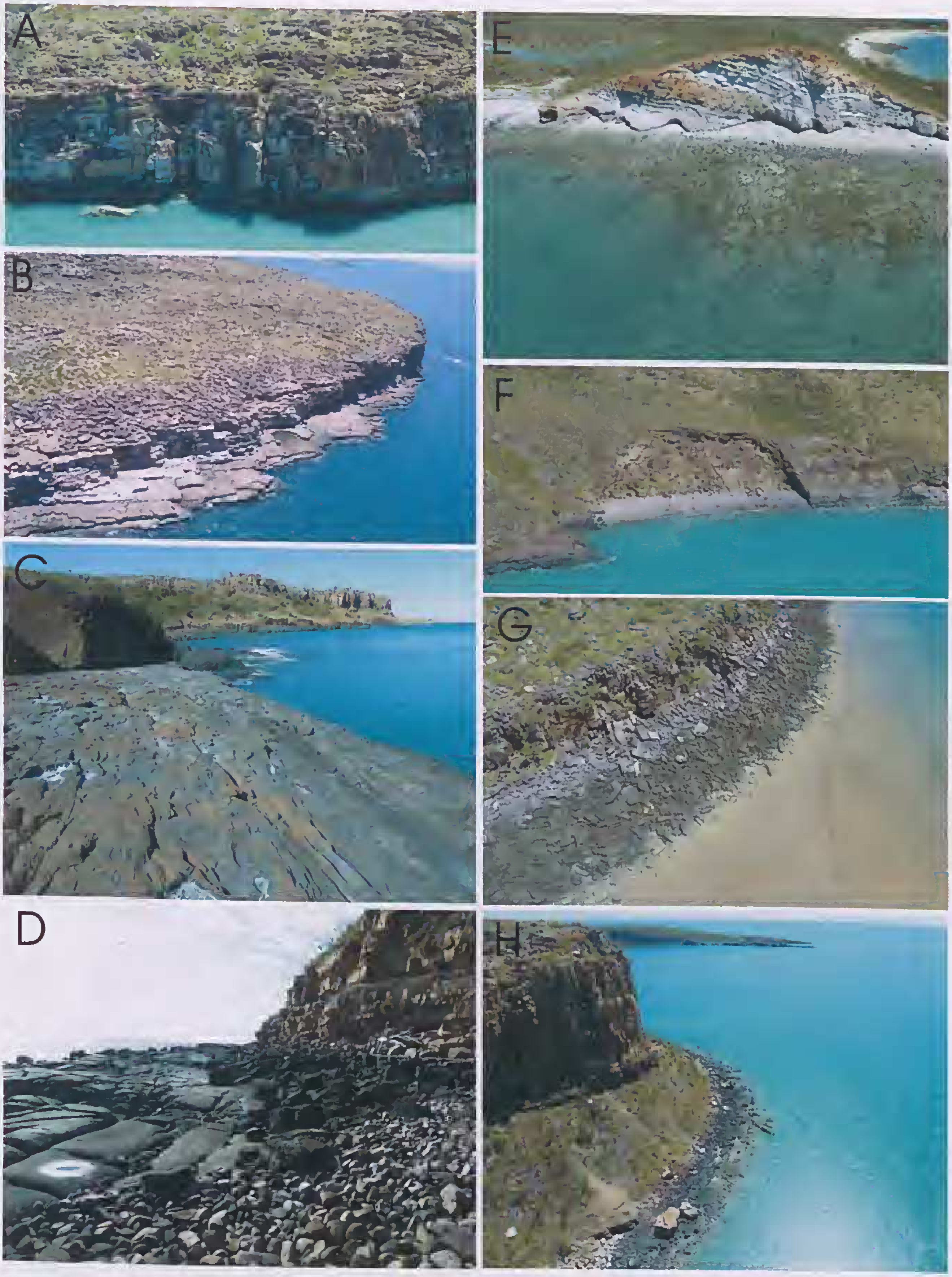

Figure 12. Oblique aerial photographs showing cliffs of the Kimberley Coast. A. Simple sandstone cliff. B. Terraced sandstone rocky shore (terraces controlled by lithology). C. Sandstone overlying basalt with platforms and terrace developed on basalt (foreground) and cliffs in sandstone (far-ground). D. Sandstone overlying jointed basalt; platform developed on basalt, and cliff developed in sandstone; rounded pebbles derived from basalt and sandstone. E. Erosion of sandstone by mass wasting; collapse apron has formed a gravelly shore deposit which descends to the low tide zone. F. Inclined sandstone strata forming plunging shore; erosion by mass wasting forms a pocket beach of sand and gravel. G. Jointed sandstone forming scree being reworked along the shore into boulder slabs. H. Sandstone overlying basalt with cliff in sandstone, and scree slope on basalt; scree develops bouldery shore deposit.

tropical environment, the macrotidal environment, wave action, the lithologies, structures of the lithologies (such as fractures and jointing), and the structural attitude of the rocks. Sandstone, siltstone, and basalt exposed at the shore are actively undergoing erosion by mass wasting, undercutting of cliff faces, joint-block erosion, salt weathering, wave erosion, tidal current erosion, and bioerosion. The suite of processes-and-products is a Nationally significant classroom for erosion processes and erosional products. They are assigned to the geoheritage category of modern landscapes and setting (active processes).

Salt weathering is a component of coastal erosion in this tropical environment, especially along the contact of the salt flats and bedrock cliffs. Salt weathering forms high-tidal pavements at about level of HAT. These pavements can be cut into basalt, dolerite, laterite, sandstone, and steeply dipping rocks. Where cut into steeply dipping rocks, the pavements expose the strata edge-on across the high-tidal flat. Similar pavements produced by salt weathering have been described from the Pilbara Coast (Semeniuk 1996). In the Kimberley region, these high-tidal pavements, indicative of macrotidal environments, range in size from microscale to leptoscale. They are coastal geomorphic features of National geoheritage significance. They are assigned to the geoheritage category of modern landscapes and setting (active processes).

There are a variety of coastal types developed in the Kimberley region, *viz.*, Types 1, 2, 5, 6, 7, 8, 9 and 12, following the classification of Brocx & Semeniuk (2010b) and, as an ensemble of coast types in the region, they comprise a Nationally significant classroom for coastal development and classification, particularly for those that are intergradational. This aspect of the Kimberley Coast generally is a macroscale to mesoscale feature, and is assigned to the geoheritage category of modern landscapes and setting (active processes).

The Kimberley Coast also locally manifests diagenetic coasts, which are generally mesoscale to microscale features. They are assigned to the geoheritage category of modern landscapes and setting (active processes). Such coastal types also occur along the Canning Coast and Pilbara Coast (Semeniuk 1996; 2008), but are not common throughout coastal mainland Australia. The diagenetic coasts (beach rock cemented ramps) along portions of the Kimberly Coast are Nationally significant.

Some of the prominent coastal outcrops along the Kimberley Coast include excellent exposures of sedimentary and volcanic rocks of the Kimberley Basin, and the rocks of the King Leopold Orogen. Examples include the cliffs of Warton Sandstone at Thurburn Bluff, at the entrance and gorge of the King George River, and Cape Rulhieres, outcrop of Carson Volcanics overlain by Warton Sandstone in the Raft Point area, at Buckle Head, and the Osborne Islands, outcrop of Carson Volcanics at Steep Island, cliffs in the King Leopold Sandstone at the Sale River, at Galley Point, and along the shores of Bigge Island, and outcrops of the Yampi Formation along cliffs between Eagle Point and Yule Entrance. Generally, the coastal outcrops are mesoscale to microscale features. They are assigned to the geoheritage category of geohistorical site, and are of National to State-wide significance.

In addition, the Kimberley Coast is well known for its scenic vistas and wilderness appeal. These are megascale to mesoscale features and, depending on location, are of International to National to State-wide importance.

A summary of the geoheritage essentials of the Kimberley Coast within the framework of the Geoheritage tool-kit is provided in Figure 13.

The significance of the geoheritage features along the Kimberley Coast – a discussion

In order to systematically assess the geoheritage significance of this region, the Kimberley Coast has been described geologically and geomorphologically and in terms of its development, as a prelude to applying the Geoheritage tool-kit.

Many aspects of the Kimberley coastal geology and geomorphology are specific to the Kimberley region, and therefore globally unique in their own right, however, there are some geological and geomorphological features that appear to be represented elsewhere globally. Prior to discussing the significance of the geoheritage features along the Kimberley Coast, it should be noted that geoheritage in the foregoing text needs to be viewed from the perspective that this region essentially is a wilderness. Elsewhere, the geological and geomorphological features which are similar are in anthropogenically modified coastal environments dominated by onshore anthropogenic land-uses and hydrochemical contamination, and shoreline harbours, canals, breakwaters, groynes, sediment management, and coastal developments and industry (Fig. 14). For the south-eastern Australian seaboard, for instance, of the three main rias, only the Hawkesbury River estuary remains relatively intact, but its bordering landscape towards its seaward edge is urbanised. Port Jackson is a heavily industrialised and urbanised harbour, and Botany Bay (the seaward portion of the Georges River ria) has an urbanised and industrialised shore and airport runway projecting into the Bay. This pattern of anthropogenic impact is similar for the rias in Spain, Ireland, and Greece. In essence, for many of the ria coasts elsewhere globally there is a strong anthropogenic overprint or influence on the coast and the only features that remain (superficially) unaltered are the geometric form of the ria (as defined by the shoreline) and some coastal vegetation. The gravel barriers developed elsewhere globally manifest a similar pattern, *e.g.*, the barrier of Chesil Bank.

To the already identified importance of the Kimberley Coast, and its unique geological and geomorphological features, is added the unspoiled wilderness setting in which *the ensemble of natural processes are still operating.*

A comparison of the Kimberley Coast in terms of its climate setting, geological features, and extent of ria coastline developed with other coasts worldwide shows that it is globally distinct (Figs 15 and 16). For instance, there are only one other ria coast developed in a tropical climate (Darwin, Australia), and it is much less extensive than the Kimberley Coast. Other ria coasts are developed along shores set in temperate climates, and without the macrotidal and cyclone influence on coastal forms and sedimentation. Rias around the world are generally not

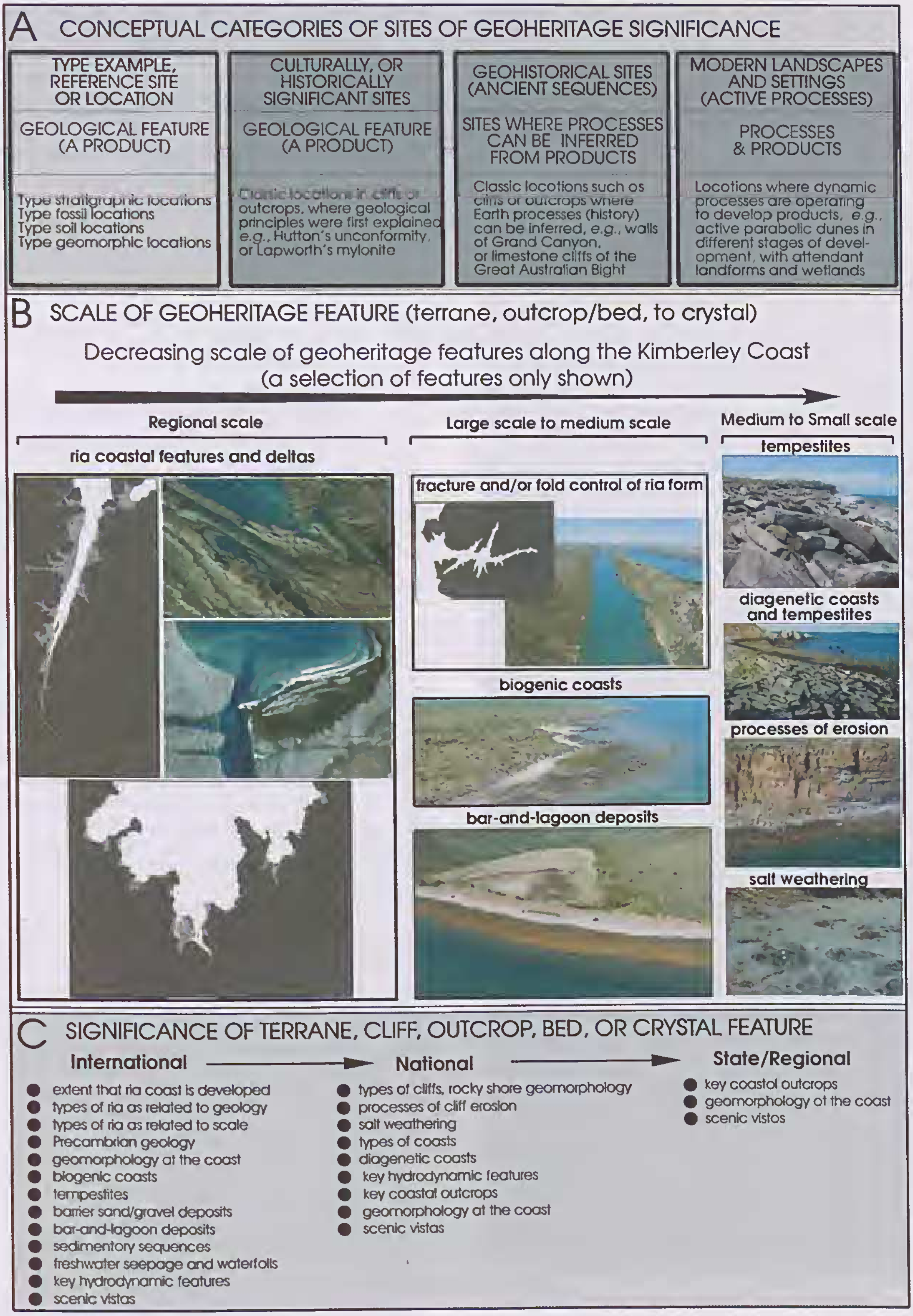

Figure 13. Application of the Geoheritage tool-kit to the Kimberley Coast. In inset A, the categories of geoheritage applicable to this area are highlighted in medium grey (the sites of cultural significance relate mainly to those of Traditional Owners). Only a selection of geoheritage features are illustrated in inset B. The full list of essential geoheritage features of the Kimberley Coast are assigned a level of significance in inset C (see text).

cut into Precambrian rock (Fig. 15). Where a ria system has been cut into Precambrian rock (Darwin), its bedrock is metamorphic rock, unlike the rias of the Kimberley Coast, and it does not present the cliffs, bluffs, and ravines that characterise the Kimberley Coast.

In comparison with the 700 km of Kimberley Coast, the coast of Galicia, Spain, presents a (simplified) length of ~ 280 km, south-western Ireland presents a length of ~ 140 km, and the south-eastern Australian rias of Hawkesbury River, Port Jackson (the Parramatta River) and the Georges River involve a combined outer coastal

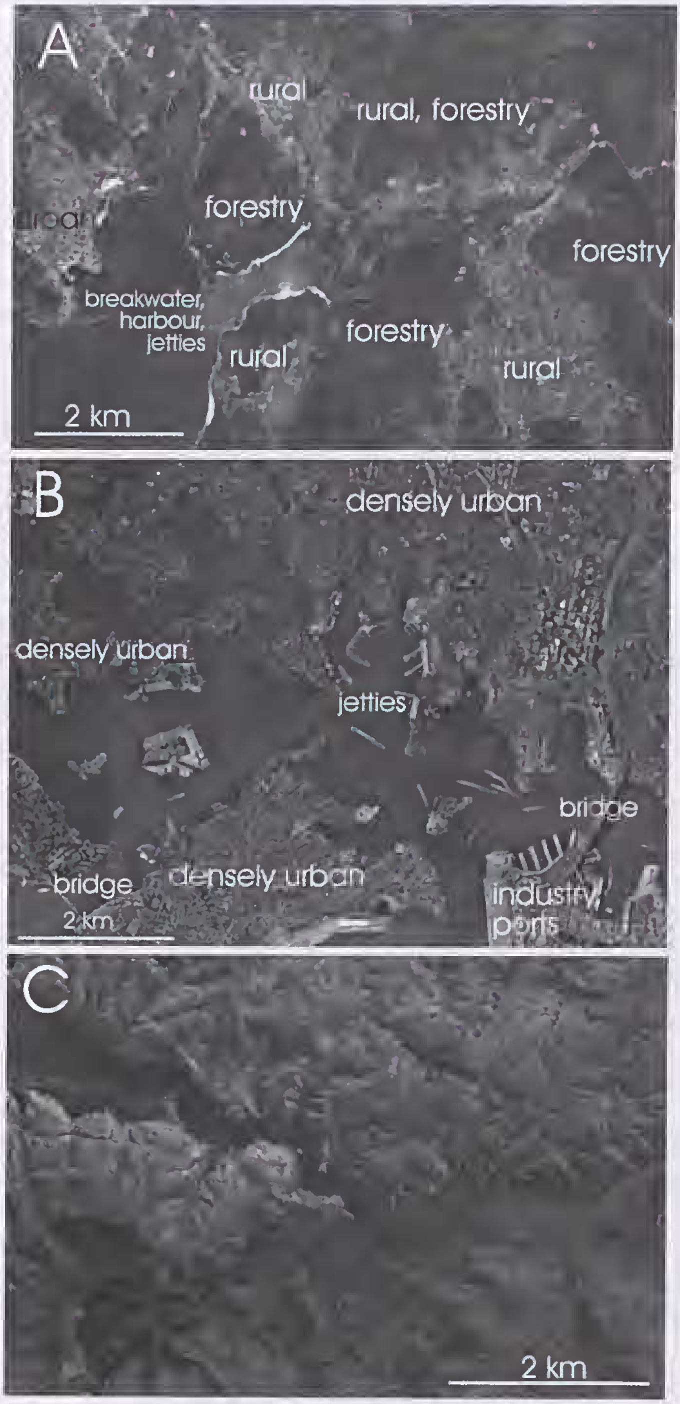

Figure 14. Anthropogenic impacts annotated on ria coasts elsewhere globally, with rural, forestry, urban, industrial, and shoreline impacts, in comparison to the Kimberley Coast. A. Coast of Galicia, Spain (the coast has been outlined in white line). B. Port Jackson, Sydney. C. Kimberley Coast. Images from Google Earth.

length of 60 km. Figure 16 shows a range of the well-known ria coasts around the World to contrast their morphology, extent, and size of rias in comparison to the rias of the Kimberley Coast. As a tropical climate ria in terms of size and morphology it is globally unique. By way of contrast, and to emphasise its extensiveness, and global uniqueness, the Kimberley Coast is compared geometrically and in terms of its size to some large fjord suites (Fig. 16). Though not rias, the fjords of northern Siberia, northern Canada, southern Chile and north-western Scotland do show indented coastlines. The Siberian suite does show broad similarity in its indentation geometry in plan, and degree of lateral extensiveness, and the south Chile suite shows fracture-controlled coastal morphology similar to the Kimberley Coast, but all the fjords are set in boreal and artic climates, and hence have wholly different coastal processes operating.

In the context of being the largest laterally extensive ria coast in the World, the Kimberley Coast presents a range of coastal forms variable in shape, size, and orientation developed on a regionally relatively consistent bedrock template, *viz.*, the rocks of the Kimberley Basin and the seaward expression of the Kimberley Plateau. As such, the ensemble of coasts cut into the rocks of the Kimberley Basin and adjoining King Leopold Orogen present a global example of the range of fracture-and-fault controlled ria coasts that can be developed therein and, ideally, the Kimberley Coast should be viewed as the global "type example" of ria coasts, and a global classroom.

Examples of rocky shore features cut into the Kimberley rocks, and contrasting rock shores cut into the rocks of the Kimberley Basin and those into the King Leopold Orogen, are uncommon in Australia, and, therefore are Nationally significant. Moreover, the rocky shores of the Kimberley Coast are not represented in other indented coasts elsewhere and, therefore the rocky shores, the ensemble of rock types exposed at the shore, and the styles of erosion effected on these rocks in a ria/archipelago setting in the Kimberley region becomes distinct and Internationally significant.

As noted earlier, the Kimberley Coast presents well-exposed and extensive coastal cliff outcrops, for over 700 km of coastal length, of Precambrian geology with exposure of sedimentary rocks and their facies changes, and the intercalated volcanic rocks. This provides a unique opportunity to investigate sedimentary conditions and crustal evolution during the Precambrian times. While there are innumerable undeformed sedimentary basins in the interior of many continents, and outcrop and dissection of these by rivers in many global localities, coasts that intersect sedimentary basins such that they are dissected with cross-basin expression of facies changes along extensive seacliffs are not so common world-wide. The entire western seaboard of North and South America, for instance, is a collision coast of post-Mesozoic age, and thus a folded, faulted, igneous-rock-intruded orogenic belt, without expression of extensive basin dissection along the coast. Similarly, the coasts of the United Kingdom and southern Europe, from Spain to Turkey, are ancient alpine zones (collision zones), with folding, faulting and splintering of sedimentary basins. The Paris Basin in France, Cretaceous to Tertiary in age,

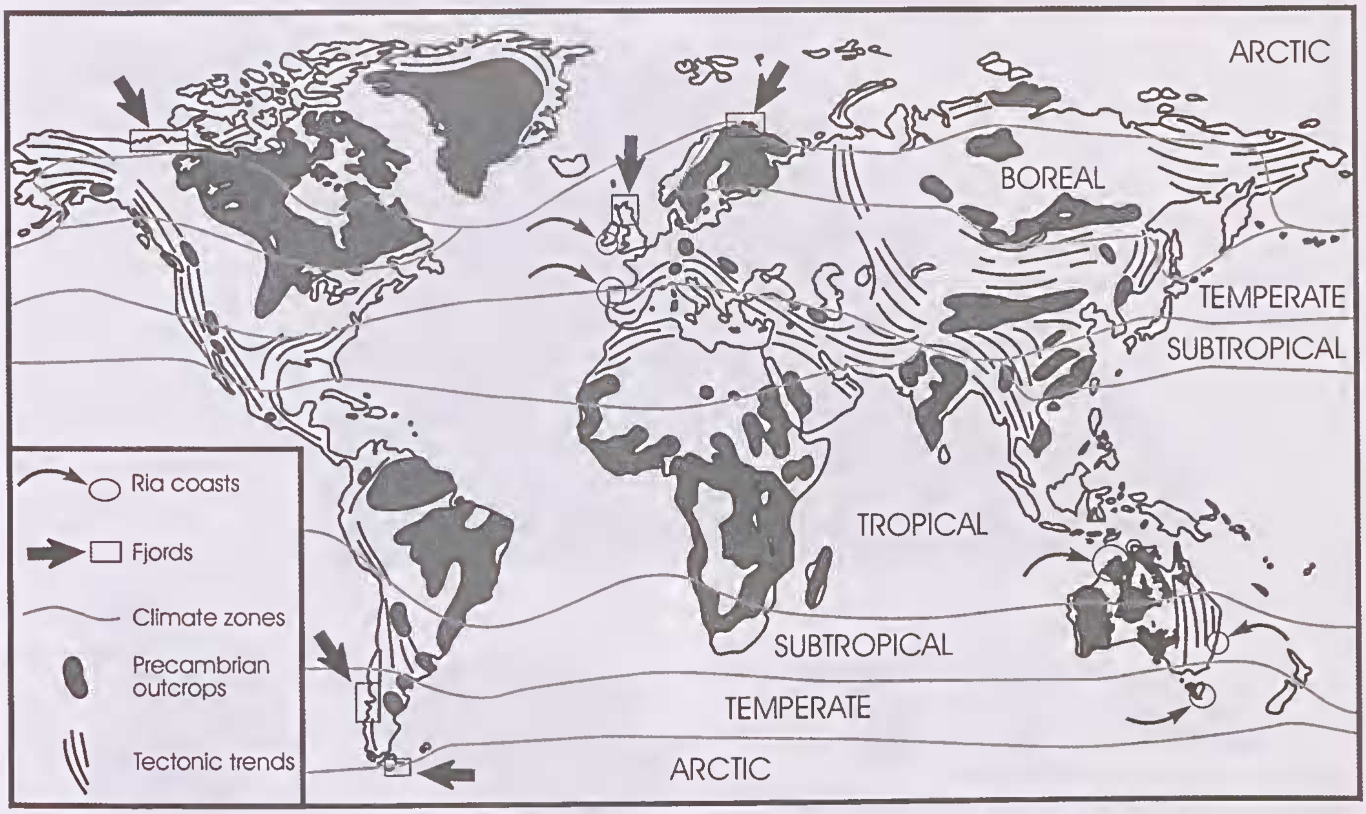

Figure 15. Precambrian rocks globally, their localised occurrence along the coast, and the climate setting of the ria coasts (Precambrian outcrops from Levin 2006; climate boundaries from Trewartha 1968). Few rias are cut into coastal exposures of Precambrian rocks. The examples of rias and fjords in Figure 16 are located as circled and boxed areas, respectively.

though largely a basin occurring inland, does find expression in its cross-basin for 200 km along a coast that dissects and reveals its intra-basinal stratigraphy, but such exposure is mainly the peripheral basin sequences of Cretaceous age (*i.e.*, chalk). The Sydney Basin of south-eastern Australia stands in contrast – it is a large basin exposed for some 500 km of coast, and though there are many intervening sandy stretches and estuaries, there is extensive development of sea cliffs, and with exposure of Permian to Triassic sequences recording marine sedimentation, glacial conditions, coal deposition, submarine lava flows, deltaic sedimentation, and fluvial and lacustrine sedimentation (Packham 1969). The sea cliffs cut into the rocks of the Sydney Basin thus expose sequences that illustrate basin evolution, sedimentary history, facies changes, and specific stratigraphic sequences and relationships across a widespread area and is a geological feature of global significance. The limestones of the Eucla Basin, mentioned earlier, cut by the cliffs along the edge of the Nullarbor Plain between Western Australia and South Australia, is of a similar nature, though restricted to sedimentary sequences of Tertiary age. Some 1000 km of the Eucla Basin is exposed along the shore (though not all of the rocks of the basin are exposed along seacliffs) to show sedimentary sequences and lateral facies changes. It also is a world-class exposure of the interior of a sedimentary basin.

In this context, the Kimberley Coast dissects a laterally extensive sedimentary basin whose rocks are well exposed almost continuously along its outer shores and the inner ria shores. Simply, as an extensively exposed sedimentary basin, the Kimberley Basin already qualifies as a region of global importance in the same manner that the Sydney Basin and Eucla Basin are significant, however, it has the added importance *of being a basin of Precambrian age* and, as such, the rocks exposed along its shores illustrate sedimentary history, facies changes, and volcanism in its content, and exposure of a Precambrian basin unparalleled in the World.

Excellent coastal exposures also occur in the megascale to microscale structures, and the lithologies of the King Leopold Orogen cropping out along the southern part of the Kimberley Coast. The folded, faulted, and metamorphosed rocks and the geological transition from rocks of the mobile zone (King Leopold Orogen) to those of the Kimberley Basin are well-exposed, and provide a world-class example of this type of geology.

The combination of bedrock types and structures, waves and tides and tropical climate and cyclones result in a suite of products that create an Internationally to Nationally significant classroom for rocky shore geomorphology. For example, the algal reefs forming shore-fringing platforms along portions of the Kimberly Coast appear to be a feature of a tropical coast that is dominated by rocky shores. The various tempestites, the barriers of gravel, especially the lithoclast gravel barriers, and the bar-and-lagoon deposits, are the result of coastal processes acting on various source materials such as coral gravel, lithoclast gravel, and beach rock slabs in a cyclone-influenced area within a fractured rock system that has produced specific coastal geometric and scalar forms. The variety of cliff types and rocky shores along the ria coast, reflect oceanographic processes, rock type, stratigraphic sequence, and geological structure.

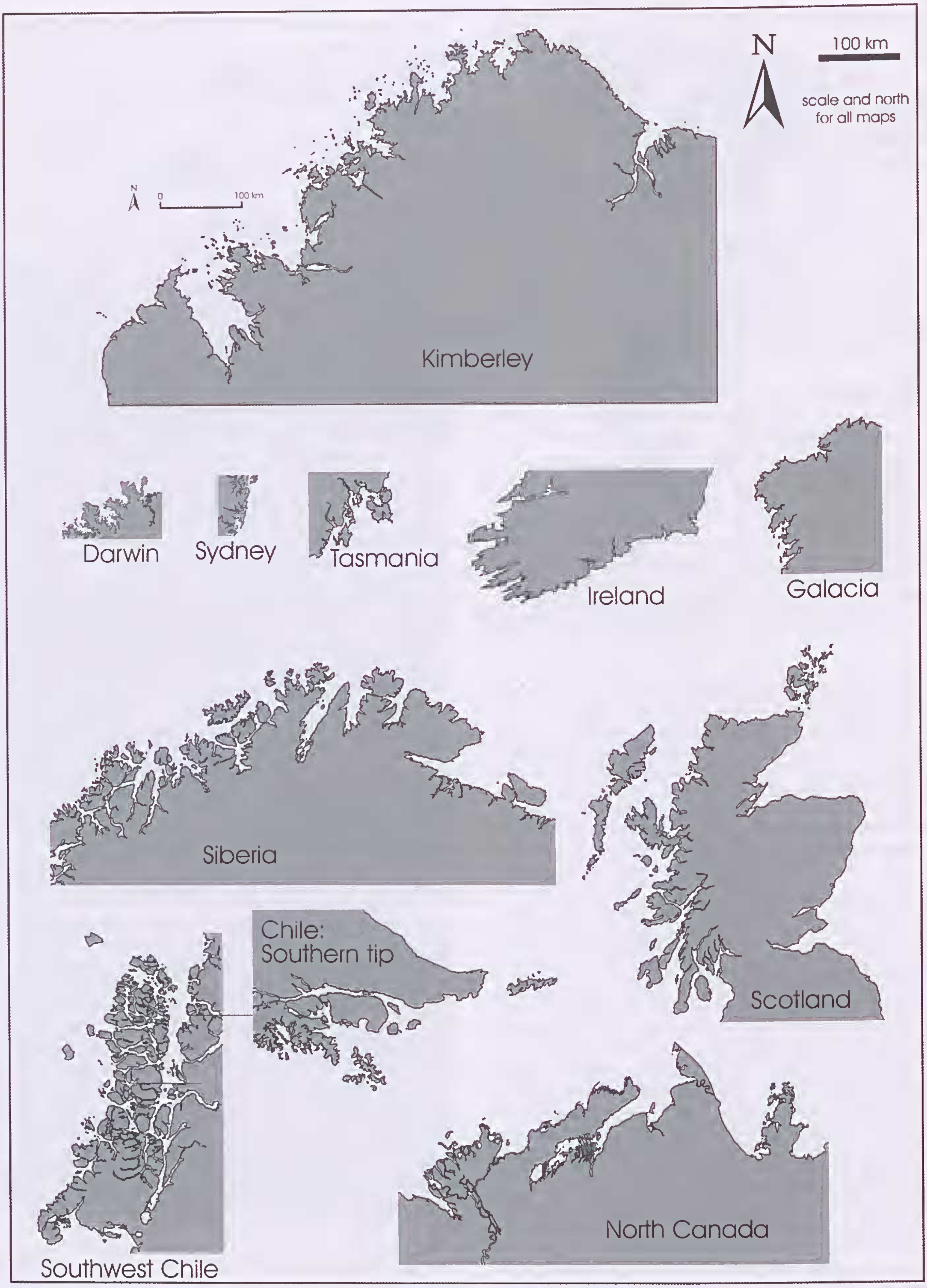

Figure 16. Comparison of the size, extent, and plan-geometry of some rias and fjords of the world in comparison to the Kimberley Coast.

Most Western Australian examples of high-tidal pavements formed by salt weathering signal macrotidal environments and processes operating at levels of the highest tides where the salinity of groundwater and soil water in a tropical environment are at their most elevated (Semeniuk 1996). In the Kimberley region this type of coastal weathering is superimposed on a variety of rock types and, as noted above, this enhances their geoheritage significance.

A generally overlooked aspect of geoheritage is hydrology. This is a subdiscipline within geology and in many respects drives diagenesis and weathering of rocks. In its own right hydrology is a fundamental part of the Earth processes and products. When frozen, water as ice is studied as an important part of geology in the field of glaciology, but while still liquid it is often ignored as a geological phenomenon (the exception being its hydrochemical and physical role in diagenesis and pedogenesis). The largest focus on water in the geological sciences is on its role as a medium that transfers energy as waves and currents and that can transport sediment or erode substrates. Previously, Brocx & Semeniuk (2007) have emphasised that hydrology as part of geology should also be captured as part of geoheritage. For the Kimberley region, along the coast, hydrology is an important part of the natural environment of extant processes because the fractured bedrock in the region acts as a major freshwater aquifer and discharges freshwater into the high-tidal environment, influencing ecological processes (specifically mangroves), cementation, and other coastal processes. This means of hinterland-to-coastal hydrological exchange is essential for some of the assemblages of mangroves along the Kimberley Coast and, in addition, results in an array of diagenetic and sedimentological products, and ecological products. Fractured sandstone overlying relatively less permeable weathered basalt results in seepage of freshwater along the basalt/sandstone interface and in the development of habitats for Kimberley rainforests (McKenzie *et al*. 1991), particularly where the interface is covered in scree.

The sediments of the Kimberley Coast are important features of the region, but need to be viewed as a regional ensemble of sediment packages. To date, sedimentologists and coastal scientists tend to view the coast in isolated segments and, as such, study in detail the coastal setting, sedimentology and stratigraphy of these isolated packages. In Western Australia, for example, Logan and colleagues studied the Shark Bay sedimentary environments (Logan *et al*. 1970, 1974) without a regional context of the larger sedimentary basin setting of the Carnarvon Basin so that adjoining sedimentary packages were not related to Shark Bay. Similarly, Johnson (1982) studied the Gascoyne River delta in isolation without relating it to the neighbouring Shark Bay sedimentary system. This is not to discredit the effort of these researchers in describing the coastal processes and products at the site-specific areas, but the inter-relationships of the sedimentary packages generally are not synthesised into a regional framework and, in the case of Shark Bay and the Gascoyne River delta, into the context of a sedimentologically-active and tectonically-active Carnarvon Basin, an aspect that is important if assessing the geoheritage significance of sedimentary systems. An exception to this case-by-case, cove-by-cove, and embayment-by-embayment approach is Fairbridge (1992) who, in a review of the literature, provided a continent-wide view of the coastal sediments of North America showing the inter-relationships of the sedimentary cells, sediment pathways, and the inter-relationships of sedimentary systems along the east and west seaboards of North America. This approach showed the inter-relatedness of sedimentary systems and could form the basis of identifying larger-scale features of geoheritage significance. Rather than view each gulf and embayment and local cove as a separate sedimentary system, the entire Kimberley Coast can be viewed as an interrelated sedimentary system wherein the various sedimentary packages are reflecting, at the largest scale, variability in bedrock geology, drainage basin configurations, drainage basin size and its setting in a given rainfall regime, coastal form, site-specific sedimentary systems, sediment supply, and coastal processes. Thus the sedimentary sequences along the Kimberley Coast located in gulfs, in tide-dominated deltas, rias, and sedimentary suites, ranging from cyclone-generated tempestites, to coastal sedimentary suites and mud-dominated sediment systems, and their associated stratigraphic packages developed by macrotidal and tropical conditions, should be viewed as a heterogeneous and patchy response to the regional abiotic and biotic processes acting on the regional geological template. In other words, there is interplay between coastal processes, coastal forms (dictated by geology, structure and drainage basins), sediment supply (dictated by drainage basins and bedrock) and sediment type. Viewed in this manner, the sedimentary packages of the Kimberley Coast as an integrated system are globally unique, and present a unified model that shows the inter-relationship of morphology, and oceanographic factors such as tide-dominated, wave-dominated, or cyclone-generated conditions, sediment delivery, the dominance of gravel *versus* sand *versus* mud, and other factors as outlined above.

Given the descriptions above of all the Geoheritage essentials, the unique and important nature of the Kimberley Coast should be viewed as an International and/or National conservation system (Step 6 of the Geoheritage tool-kit), essentially a mega-geopark, within which there are many features of International significance, thus integrating the many smaller-scale features of geology and geomorphology into a single geoconservation unit, *i.e.*, the geopark. In the UNESCO definition of a geopark, the Kimberley Coast qualifies in containing numerous "*geological heritage sites of special scientific importance*". The various components of the geoheritage of the area should be viewed not in isolation, as type locations, or "best example of a given feature", but as the integrated system of geological products and as integrated systems of processes-and-products. Coastal evolution and form, its associated sedimentary evolution, and the exposure of Precambrian stratigraphy are examples of these principles. Algal reef, diagenetic coasts, and freshwater seepage are further examples.

As a remote wilderness area, that has not previously described for assessing sites of Geoheritage significance, the Geoheritage tool-kit has been applied to identify and rank features of geoheritage significance using an inventory-based approach that assigns a level of significance to geological features regardless of their scale and within a framework of the broadest possible definition of the Science of Geology. It is not possible to include all geological features of microscale and leptoscale at this stage and as more geological studies of this region are undertaken, it is assumed that this initial inventory will be revised, updated, and supplemented with information that will lead to the appropriate conservation category, and management.

The Kimberley Coast can in fact be used as a case study for inventory based assessment of Geoheritage significance globally. This is because it contains a wide variety of geological and geomorphological features, varying in significance from International to State-wide, and this study demonstrates how the Geoheritage tool-kit can be applied to geological sites, or regions, to determine geoheritage values for conservation and management. However, it should be appreciated that the Kimberley Coast has a large number of geological and coastal geomorphological features that are of International significance in a tropical wilderness setting and it is unlikely that there are many other Regions elsewhere with the number and range and scope of sites of geoheritage significance found on the Kimberley Coast.

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